



US011246256B2

(12) **United States Patent**  
**Snyder et al.**

(10) **Patent No.:** **US 11,246,256 B2**  
(45) **Date of Patent:** **Feb. 15, 2022**

(54) **MACHINE VISION CONTROL SYSTEM FOR PRECISION AGRICULTURE**

A01B 63/02; A01B 71/002; A01B 71/00;  
G06K 9/00657; G06K 9/627; G06K  
9/0063; G06K 9/00624; G06K 9/00;  
G06K 9/6268; G06K 9/6267; G06K 9/62;  
A01M 21/02; A01M 21/00

(71) Applicant: **Stout Industrial Technology, Inc.**,  
Salinas, CA (US)

See application file for complete search history.

(72) Inventors: **Steven T. Snyder**, Salinas, CA (US);  
**Jeffrey L. Antle**, Salinas, CA (US)

(56) **References Cited**

(73) Assignee: **Stout Industrial Technology, Inc.**,  
Salinas, CA (US)

U.S. PATENT DOCUMENTS

(\* ) Notice: Subject to any disclaimer, the term of this  
patent is extended or adjusted under 35  
U.S.C. 154(b) by 0 days.

2,920,707 A 1/1960 Oliphant  
3,851,451 A 12/1974 Agness et al.  
(Continued)

FOREIGN PATENT DOCUMENTS

(21) Appl. No.: **17/172,006**

EP 1116427 9/2004  
EP 3278649 8/2017  
(Continued)

(22) Filed: **Feb. 9, 2021**

(65) **Prior Publication Data**

US 2021/0243940 A1 Aug. 12, 2021

**Related U.S. Application Data**

(60) Provisional application No. 63/074,544, filed on Sep.  
4, 2020, provisional application No. 62/972,641, filed  
(Continued)

OTHER PUBLICATIONS

John Deere; 600FD-Flexible Draper Active Header Height Control  
(AHHC) Quick Reference Guide; Downloaded from the Internet on  
Feb. 4, 2020 from <https://www.deere.com/assets/pdfs/common/parts-and-service/manuals-training/600FD-Flexible-Draper.pdf>.  
(Continued)

(51) **Int. Cl.**

**A01B 71/02** (2006.01)  
**A01B 63/00** (2006.01)

(Continued)

*Primary Examiner* — Christopher J. Novosad

(74) *Attorney, Agent, or Firm* — Frost Brown Todd LLC;  
Dennis S. Schell

(52) **U.S. Cl.**

CPC ..... **A01B 71/02** (2013.01); **A01B 63/002**  
(2013.01); **A01B 63/008** (2013.01); **A01B**  
**63/10** (2013.01);

(Continued)

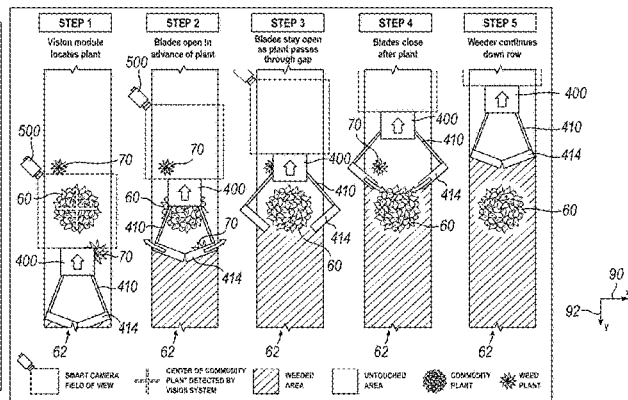
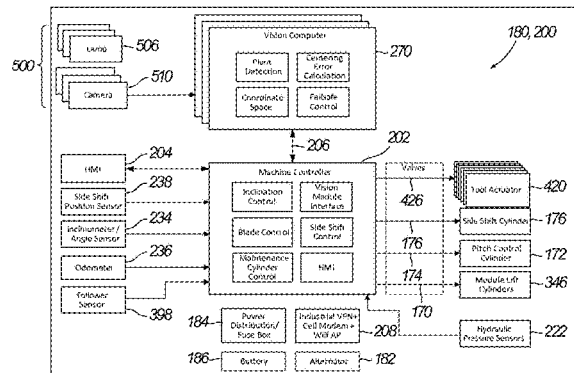
(57) **ABSTRACT**

An illustrative control system for an precision agricultural  
implement includes a controller having a convolutional  
neural network, a machine vision module, a plurality of  
sensors, and a plurality of actuators in communication with  
the controller, the plurality of actuators including a plurality  
of agricultural tool actuators.

(58) **Field of Classification Search**

CPC ..... A01B 79/005; A01B 63/008; A01B 63/10;  
A01B 79/00; A01B 63/002; A01B 63/00;

**21 Claims, 17 Drawing Sheets**



**Related U.S. Application Data**

on Feb. 10, 2020, provisional application No. 62/971, 991, filed on Feb. 9, 2020.

(51) **Int. Cl.**

**A01B 79/00** (2006.01)  
**A01B 63/10** (2006.01)  
**A01M 21/02** (2006.01)  
**G06K 9/00** (2006.01)  
**G06K 9/62** (2006.01)

(52) **U.S. Cl.**

CPC ..... **A01B 79/005** (2013.01); **A01M 21/02**  
(2013.01); **G06K 9/00657** (2013.01); **G06K**  
**9/627** (2013.01)

## (56)

**References Cited**

## U.S. PATENT DOCUMENTS

6,374,155 B1 4/2002 Wallach et al.  
9,980,421 B1 5/2018 Hammes  
10,008,035 B1 6/2018 Redden et al.  
10,390,481 B1 8/2019 Brown et al.  
2002/0095239 A1 7/2002 Wallach et al.  
2002/0178710 A1 12/2002 Engelstad et al.  
2005/0126144 A1 6/2005 Koselka et al.  
2006/0012673 A1 1/2006 Koselka et al.  
2006/0213167 A1 9/2006 Koselka et al.  
2007/0195160 A1 8/2007 Koselka et al.  
2008/0155954 A1 7/2008 Schlipf  
2009/0210119 A1 8/2009 Poulsen  
2010/0037582 A1 2/2010 Sauerwein  
2011/0137456 A1 6/2011 Koselka et al.  
2011/0211733 A1 9/2011 Schwartz  
2012/0048160 A1 3/2012 Adams et al.  
2012/0060730 A1 3/2012 Bassett  
2013/0204437 A1 8/2013 Koselka et al.  
2013/0235183 A1 9/2013 Redden  
2013/0238201 A1 9/2013 Redden  
2013/0269456 A1 10/2013 Jones  
2014/0021267 A1 1/2014 Sudduth et al.  
2015/0015697 A1 1/2015 Redden et al.  
2015/0027040 A1 1/2015 Redden  
2015/0027041 A1 1/2015 Redden  
2015/0027043 A1 1/2015 Redden  
2015/0027044 A1 1/2015 Redden  
2015/0051779 A1 2/2015 Camacho-Cook et al.  
2015/0150188 A1 6/2015 Stroot et al.  
2015/0237790 A1 8/2015 Redden et al.  
2015/0237791 A1 8/2015 Bassett et al.  
2015/0245554 A1 9/2015 Redden  
2016/0066505 A1 3/2016 Bakke et al.  
2016/0157415 A1 6/2016 Cavender-Bares et al.  
2016/0255778 A1 9/2016 Redden et al.  
2017/0206415 A1 7/2017 Redden  
2017/0219711 A1 8/2017 Redden et al.  
2017/0227969 A1 8/2017 Murray et al.  
2017/0251589 A1 9/2017 Tippery et al.  
2017/0290260 A1 10/2017 Redden et al.  
2017/0359943 A1 12/2017 Calleija et al.  
2018/0116094 A1 5/2018 Redden  
2018/0121725 A1 5/2018 Redden et al.  
2018/0121726 A1 5/2018 Redden et al.  
2018/0153084 A1 6/2018 Calleija et al.  
2018/0286117 A1 10/2018 Redden et al.

2018/0325019 A1 11/2018 Connell et al.  
2018/0330166 A1 11/2018 Redden et al.  
2019/0064363 A1 2/2019 Redden et al.  
2019/0188847 A1 6/2019 Gonzalez et al.  
2019/0239502 A1 8/2019 Palomares et al.  
2019/0261581 A1 8/2019 Redden et al.  
2019/0357520 A1 11/2019 Redden et al.  
2019/0362146 A1 11/2019 Polzounov et al.  
2019/0387678 A1 12/2019 Knopf et al.  
2020/0073389 A1 3/2020 Flajolet et al.  
2020/0296875 A1 9/2020 Calleija et al.

## FOREIGN PATENT DOCUMENTS

EP 3278649 2/2018  
KR 101808686 12/2017  
WO 2016099386 6/2016  
WO 2016128688 8/2016  
WO 2020154515 7/2020

## OTHER PUBLICATIONS

Yangmin XIE, Andrew G. Alleyne, Ashley GREER and Dustin Deneault; Fundamental Limits in Combine Harvester Header Height Control; Article in Journal of Dynamic Systems Measurement and Control; Downloaded from the Internet on Feb. 4, 2020 from [https://www.researchgate.net/publication/254261361\\_Fundamental\\_Limits\\_in\\_Combine\\_Harvester\\_Header\\_Height\\_Control](https://www.researchgate.net/publication/254261361_Fundamental_Limits_in_Combine_Harvester_Header_Height_Control).  
John Deere; HydraFloat integrated suspension system improves ground following article; Downloaded from the Internet on Feb. 4, 2020 from [http://salesmanual.deere.com/sales/salesmanual/en\\_NA/combindes\\_headers/2011/feature/platforms\\_headers/draper/600d\\_hydrafloat\\_integrated\\_suspension\\_system.html](http://salesmanual.deere.com/sales/salesmanual/en_NA/combindes_headers/2011/feature/platforms_headers/draper/600d_hydrafloat_integrated_suspension_system.html).  
Garford Robo-Pilot product page; Downloaded from the Internet on Feb. 4, 2020 from <https://garford.com/products/robo-pilot/>.  
Garford Hoes Inter-row cultivation equipment product page; Downloaded from the Internet on Feb. 4, 2020 from <https://www.nigelquinnams.co.uk/wp-content/uploads/2020/01/Interrow-hoes.pdf>.  
Garford; Robocrop Precision guided high speed hoes product page; Downloaded from the Internet on Feb. 4, 2020 from <https://garford.com/wp-content/uploads/2018/07/Robocrop-Consolepdf>.  
F Poulsen Aps Engineering; Manual for Mechanical Weeding Robot Robovator; Downloaded from the Internet on Feb. 4, 2020 from [http://www.visionweeding.com/ROBOVATOR%20MANUAL\\_9\\_english.doc.pdf](http://www.visionweeding.com/ROBOVATOR%20MANUAL_9_english.doc.pdf).  
Ferrari Costruzioni Meccaniche; Remoweed product page; Downloaded from the Internet on Feb. 4, 2020 from [https://ferrariostruzioni.com/modules/cws\\_downloaditem/documents/d7dab4eb04e70c3995600c962b79877ad9d14dddREMOWEED\\_web.pdf](https://ferrariostruzioni.com/modules/cws_downloaditem/documents/d7dab4eb04e70c3995600c962b79877ad9d14dddREMOWEED_web.pdf).  
Garford; Roborop Inrow Inter-row and Inter-Plant Weeder product page; Downloaded from the Internet on Feb. 4, 2020 from <https://garford.com/wp-content/uploads/2018/07/Robocrop-InRow-.pdf>.  
Steketee; IC-Weeder Intelligent hoeing machine with single plant detection brochure; Downloaded from the Internet May 11, 2021 from <https://pdf.agriexpo.online/pdf/machinefabriek-steketee-bv/ic-weeder/169628-29429.html>.  
Planttape Inc.; Three Point Planter; Downloaded from the Internet on May 11, 2021 from <https://www.planttape.com/equipment/3-point-planter/>.  
Search Report and Written Opinion dated Apr. 28, 2021 for PCT/US21/17292.  
Written Opinion of the International Searching Authority dated Apr. 28, 2021 for PCT/US21/17292.

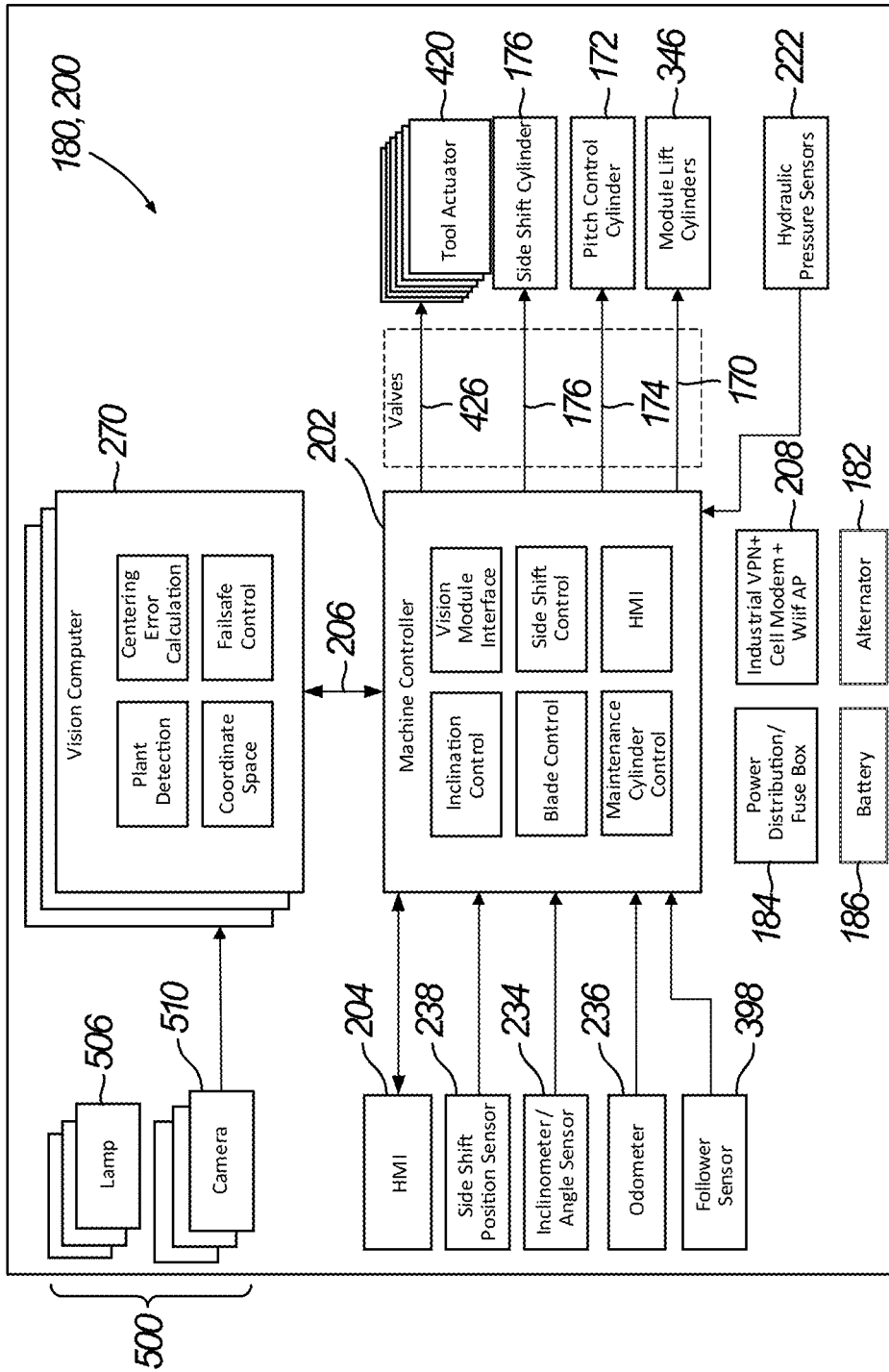


FIG. 1

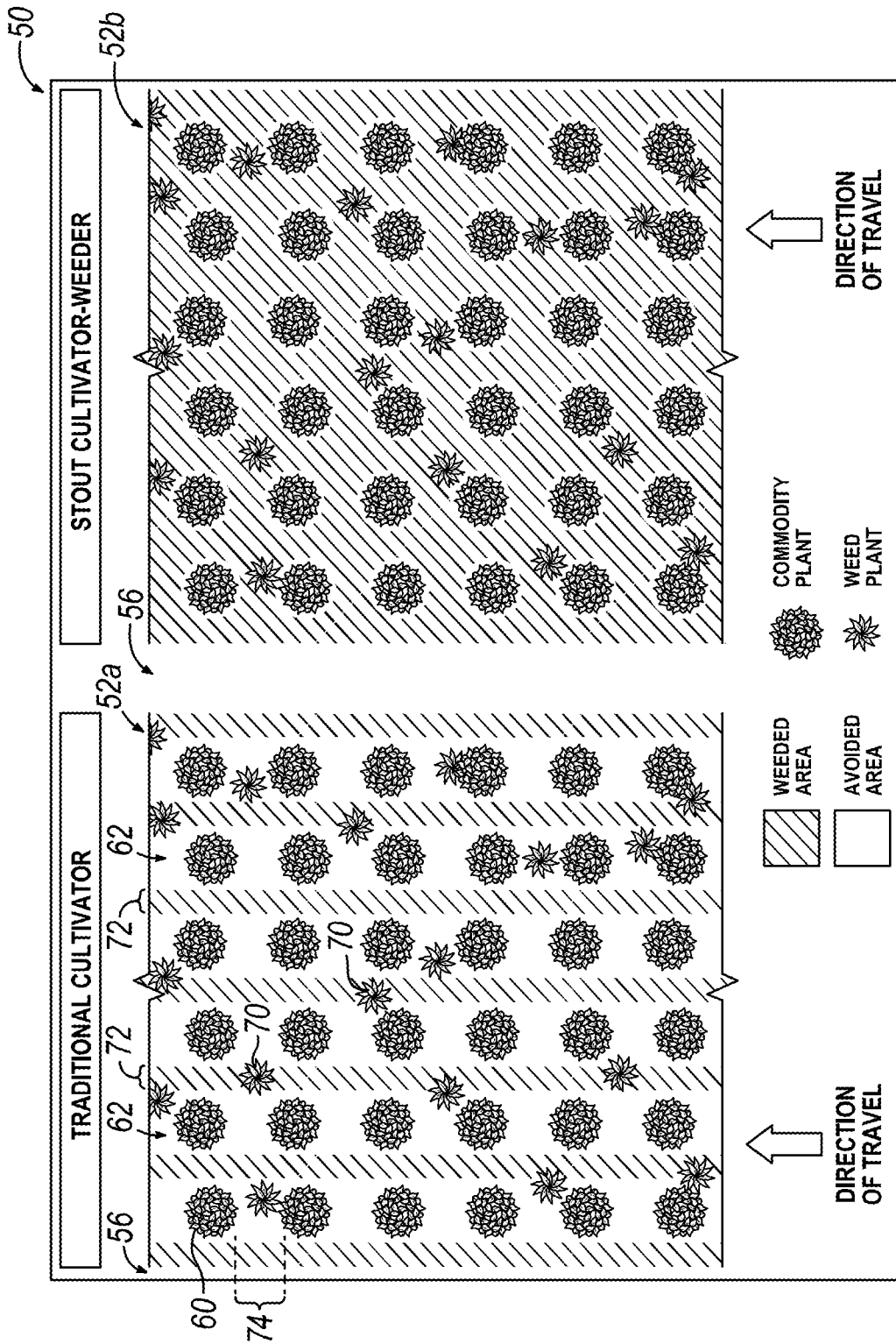


FIG. 2

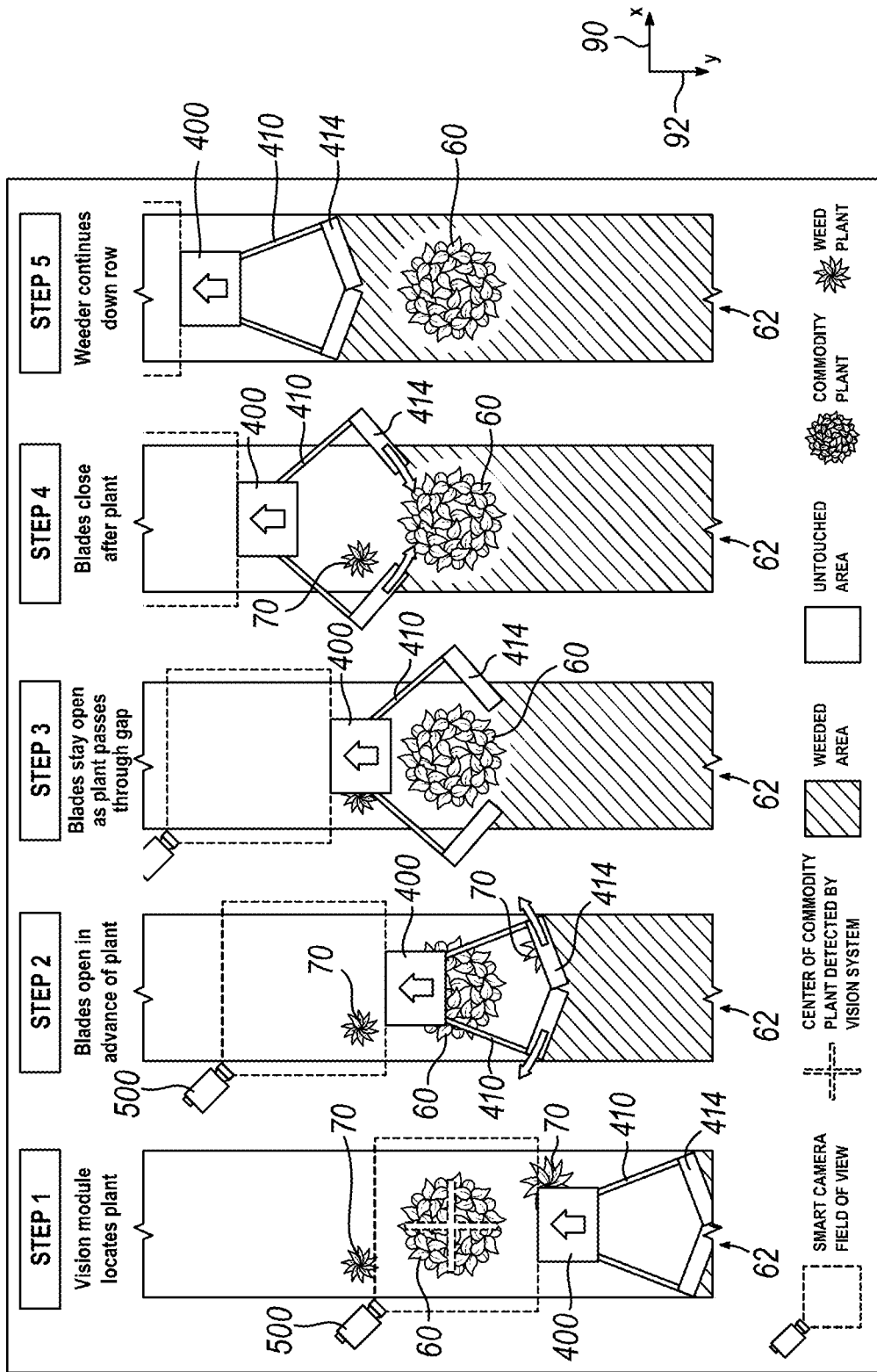


FIG. 3

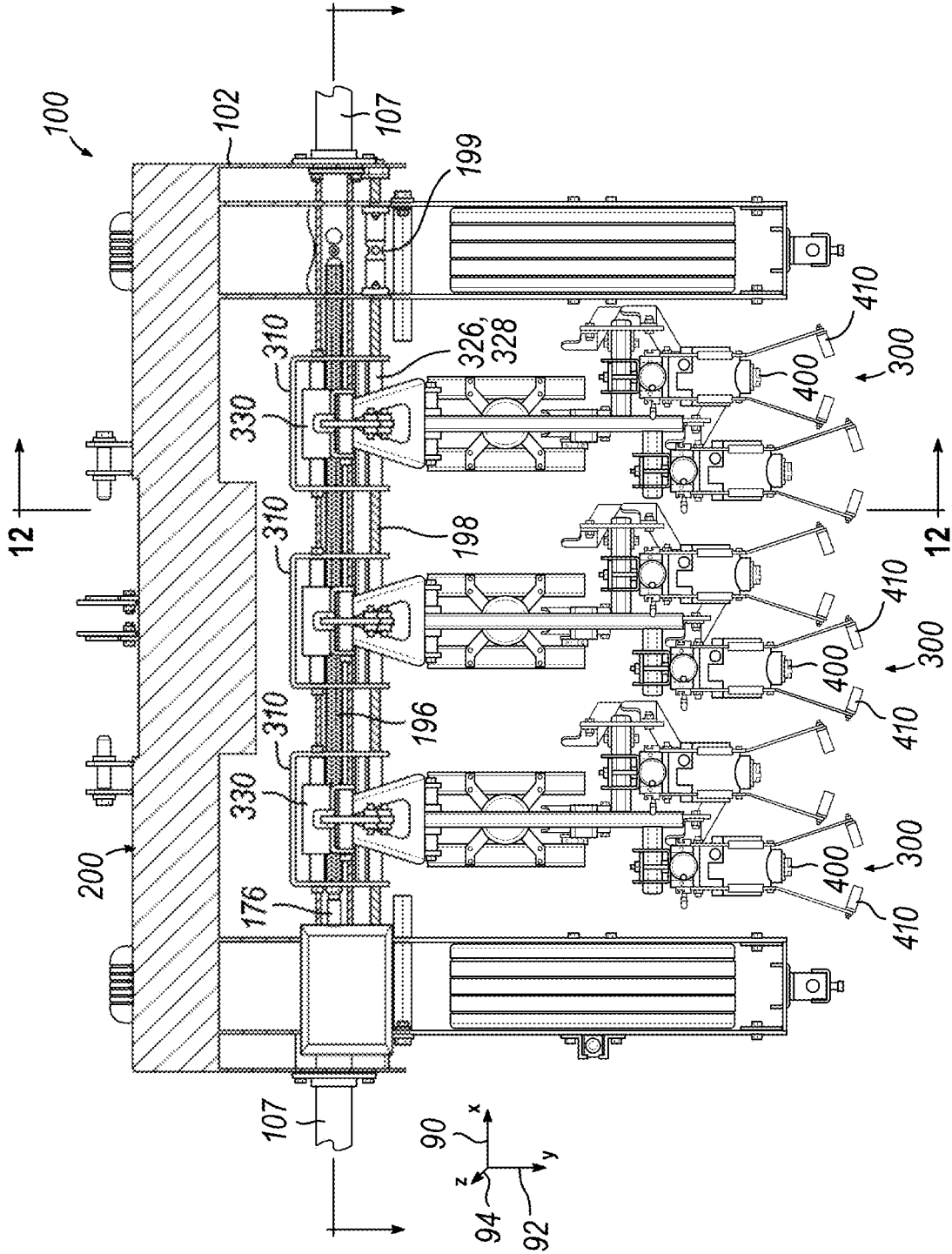


FIG. 4A

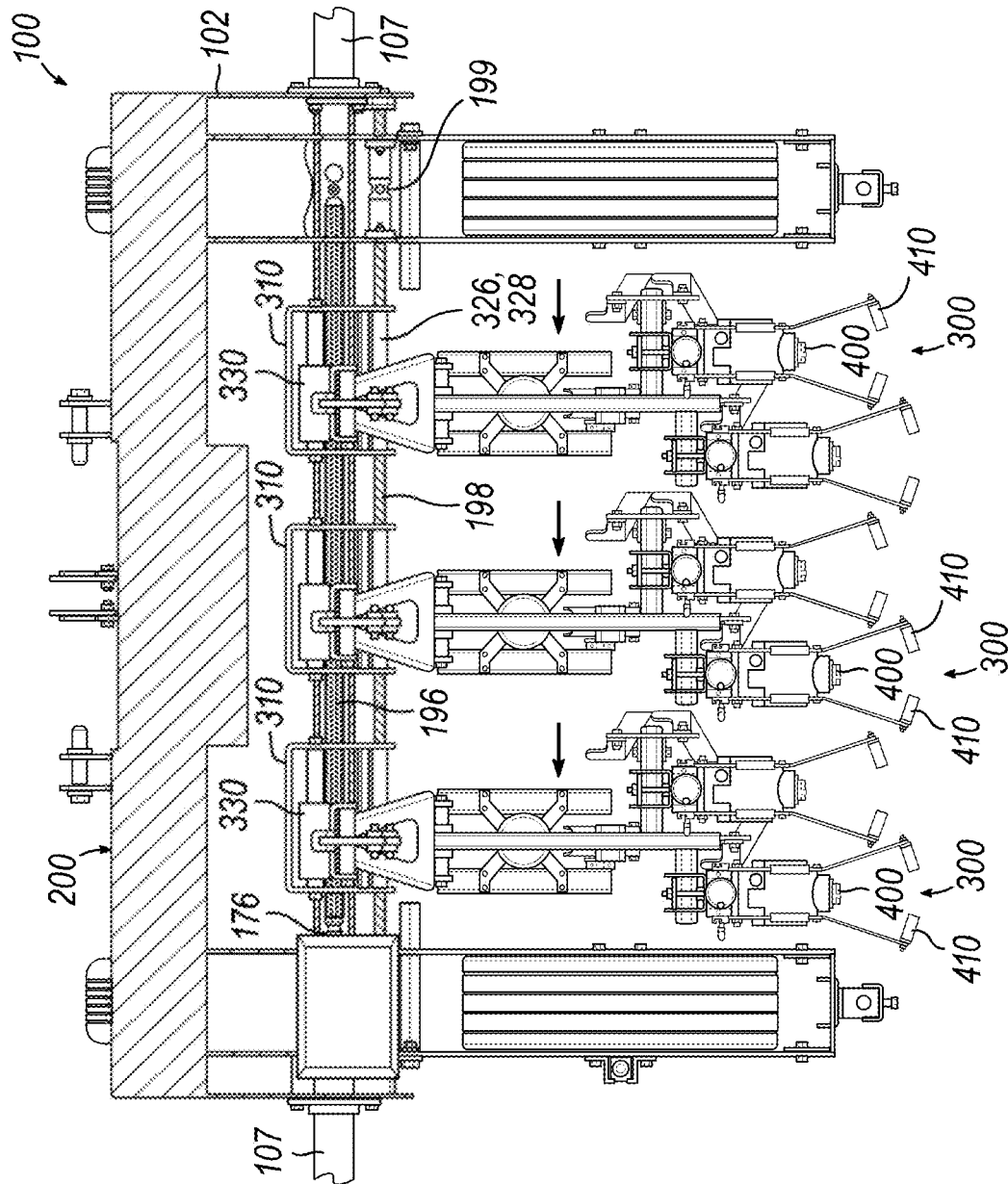


FIG. 4B

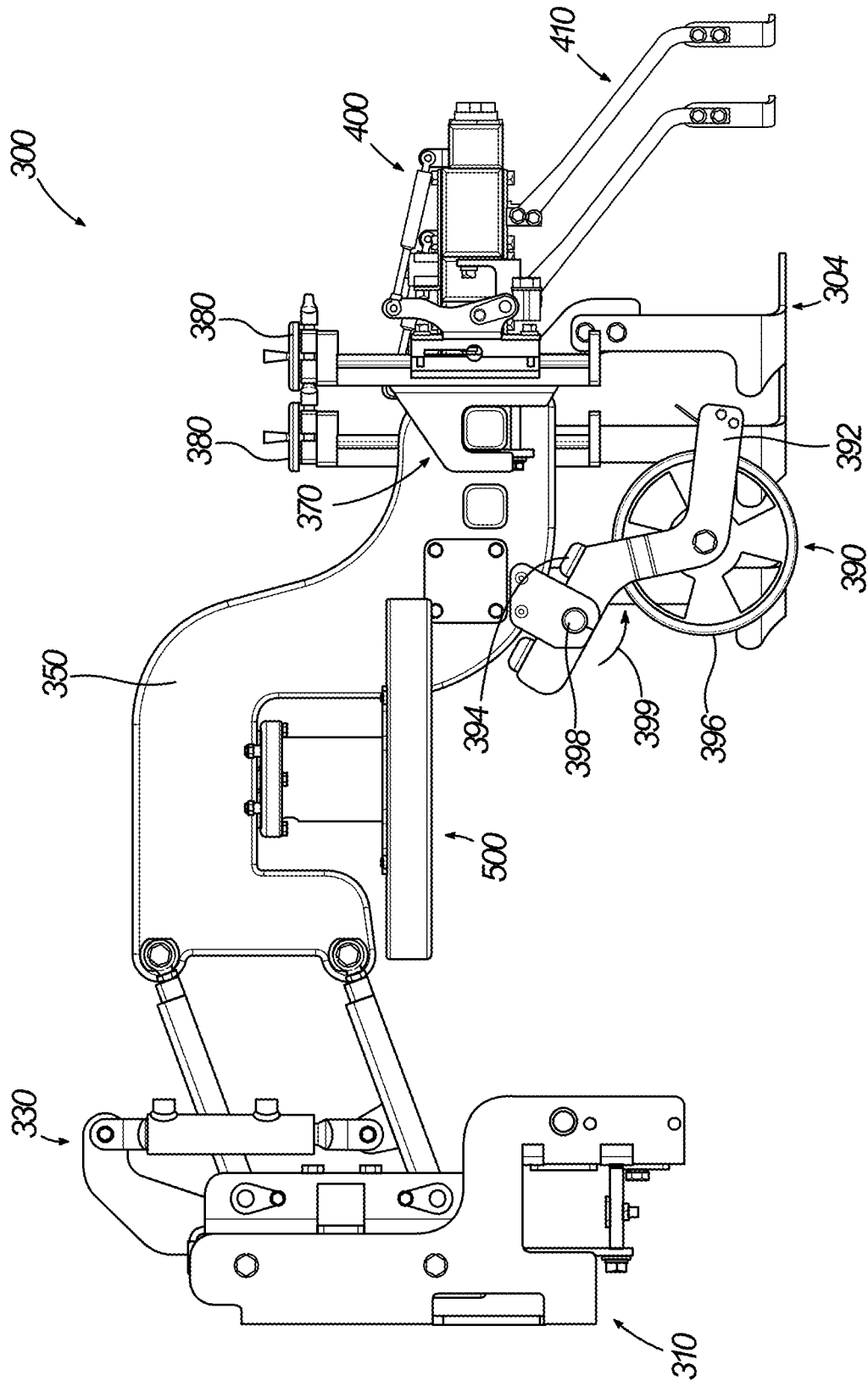


FIG. 5

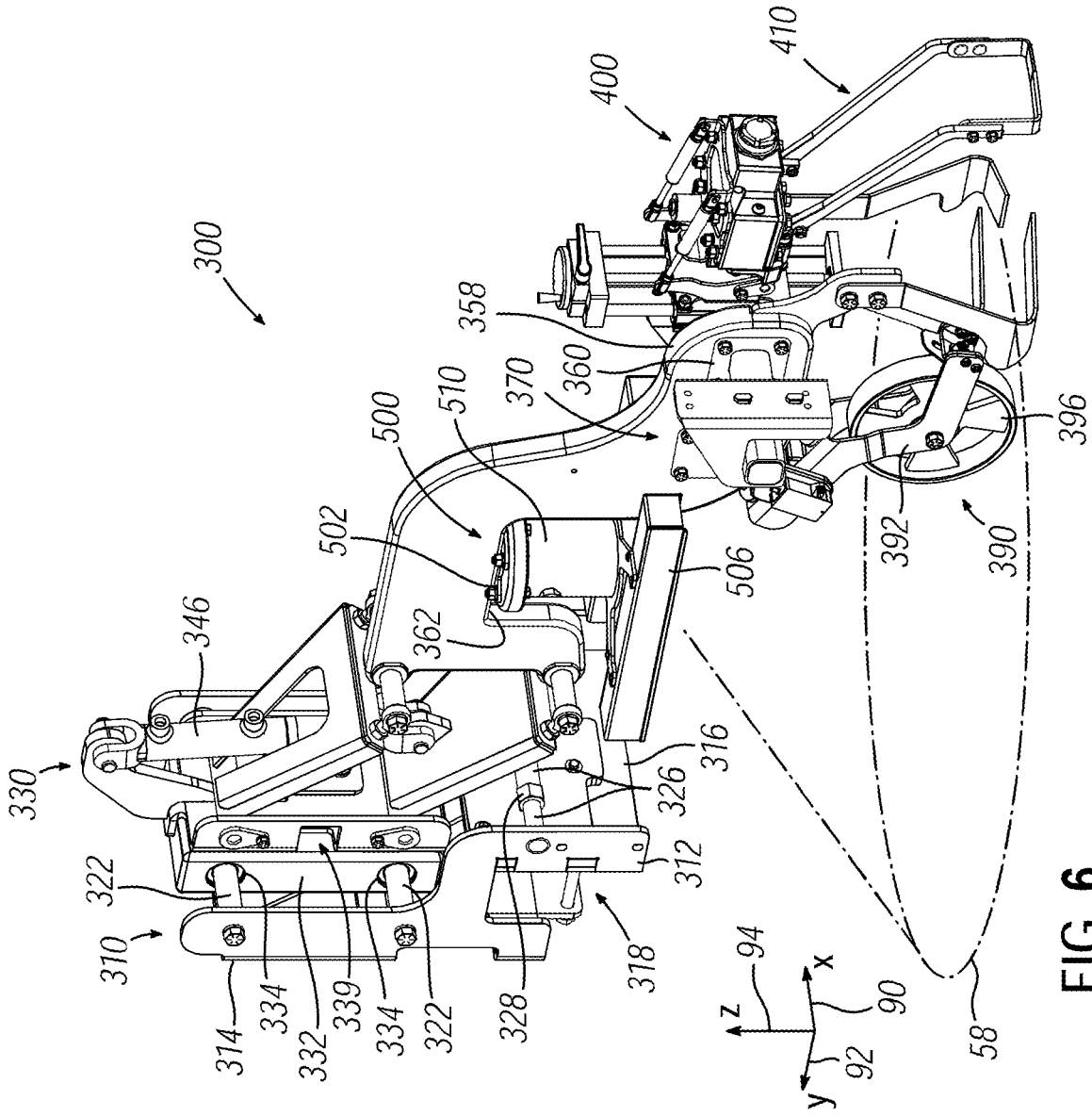


FIG. 6

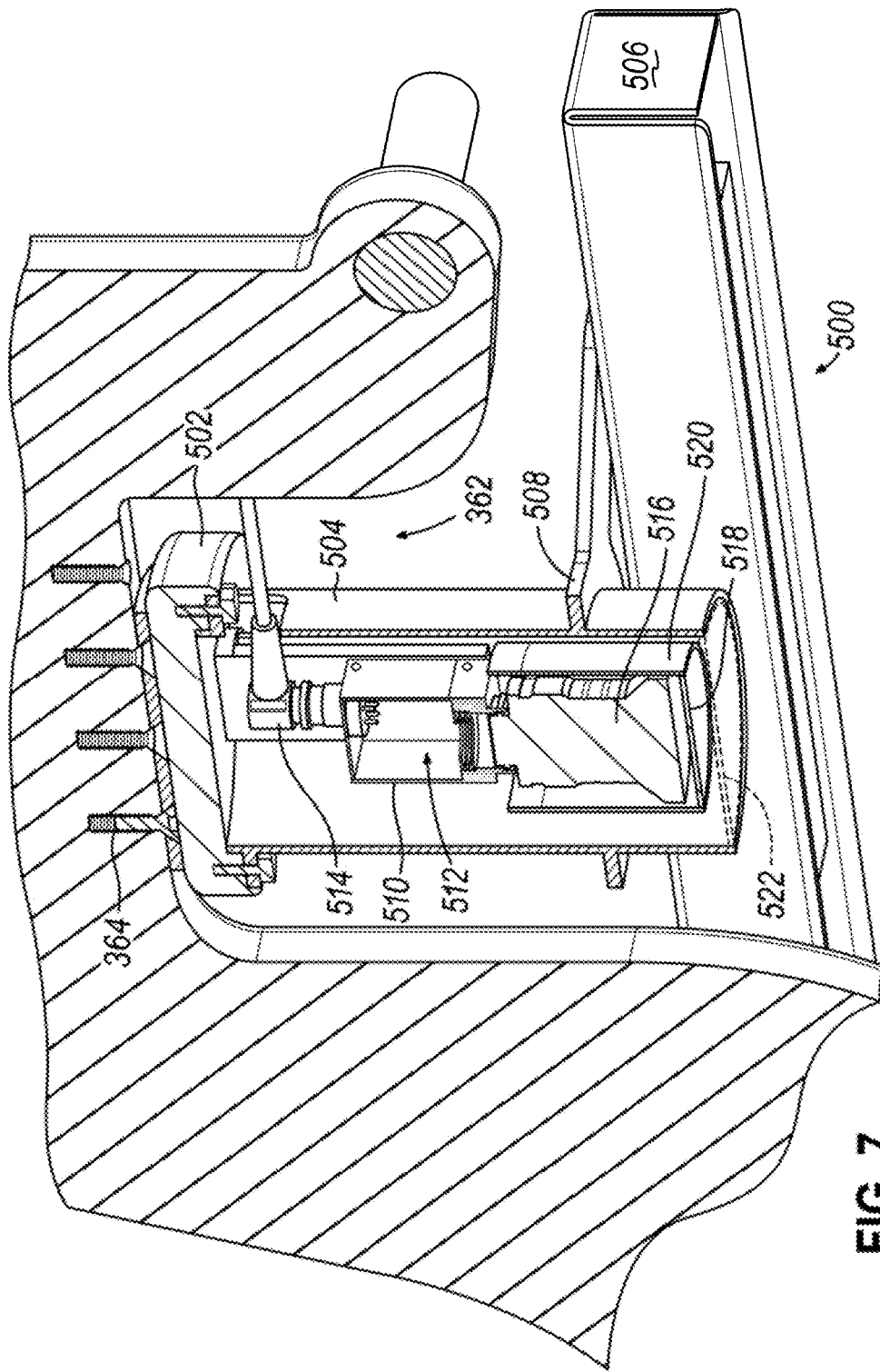


FIG. 7

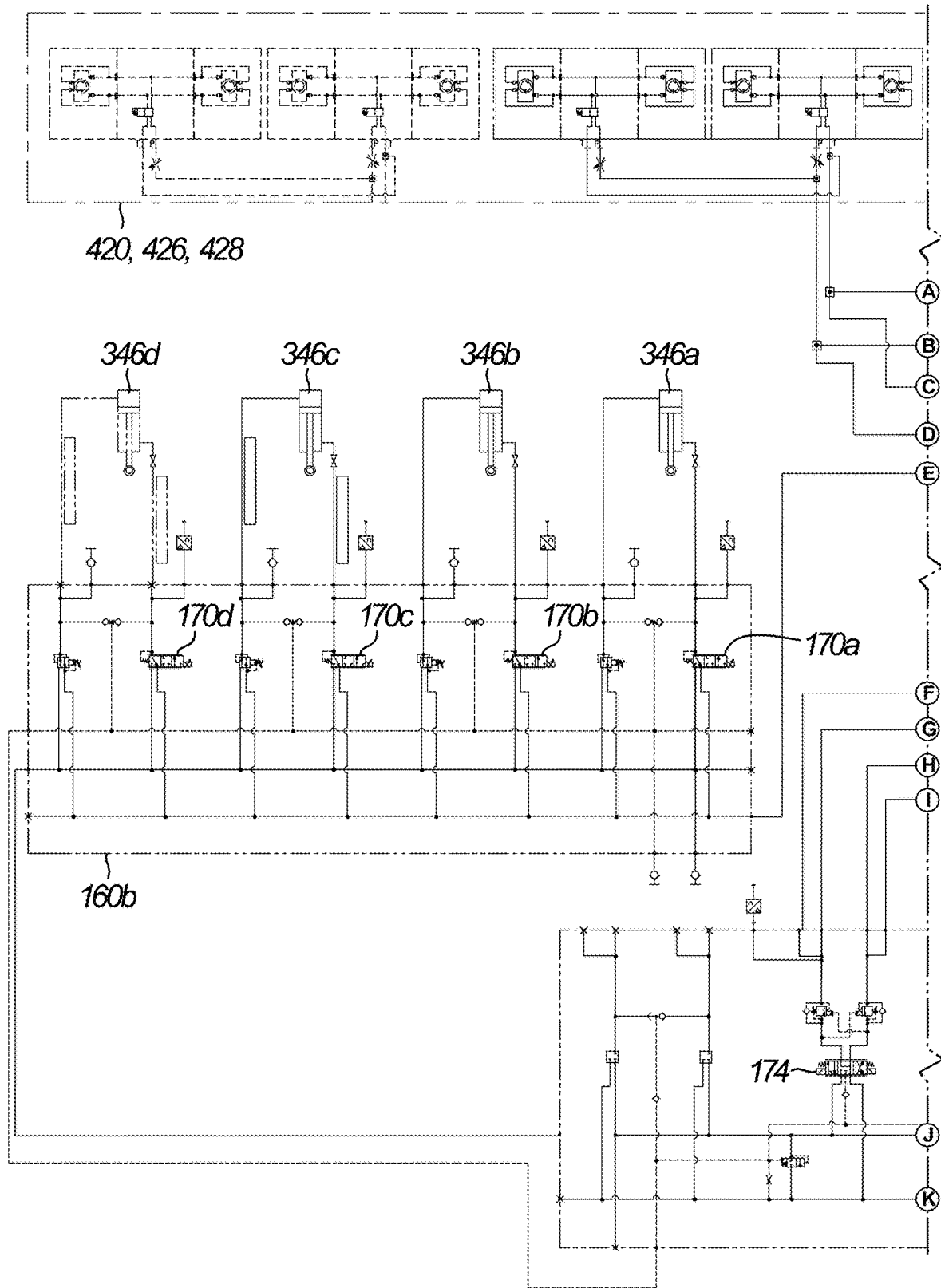


FIG. 8A

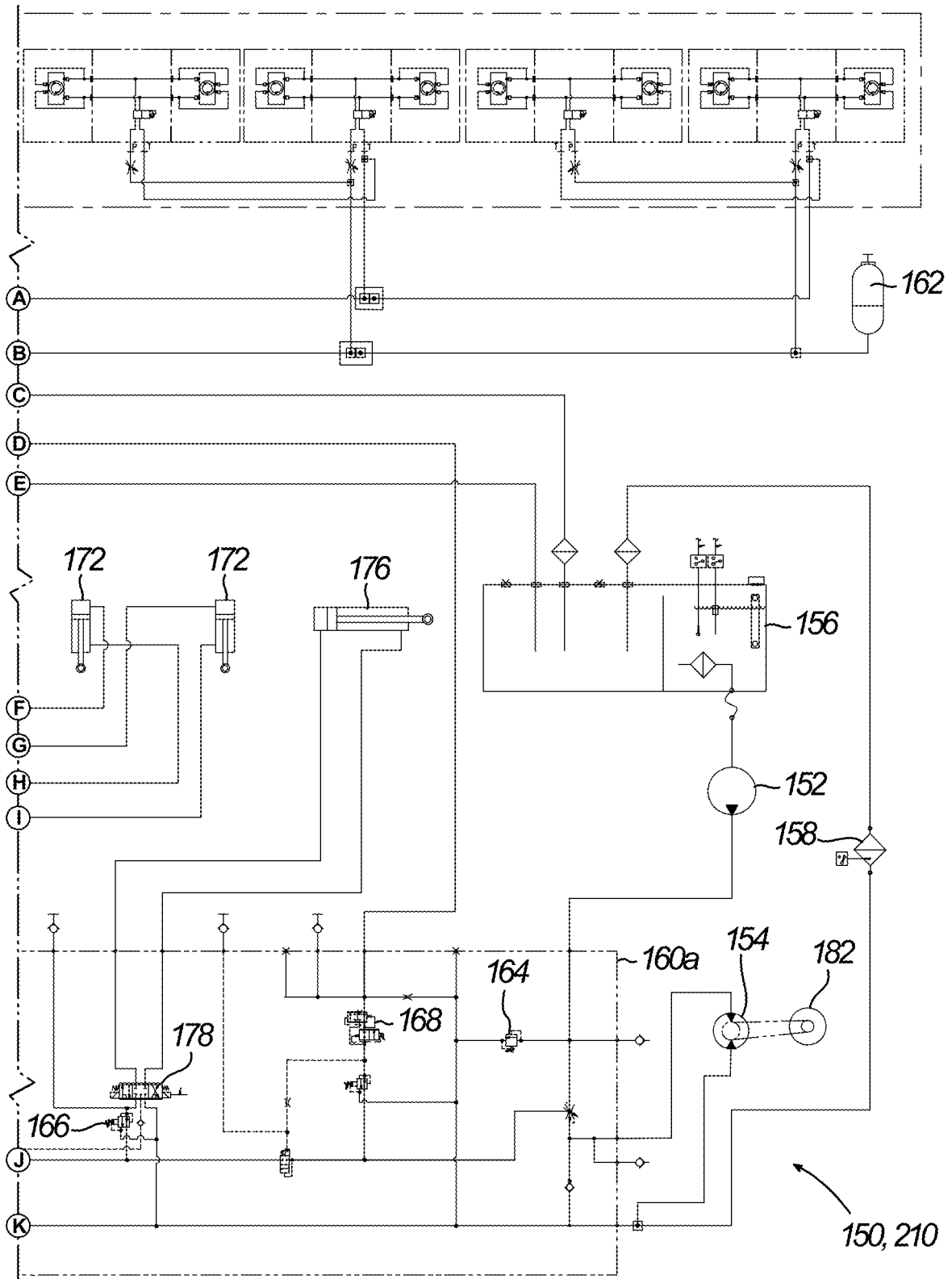


FIG. 8B

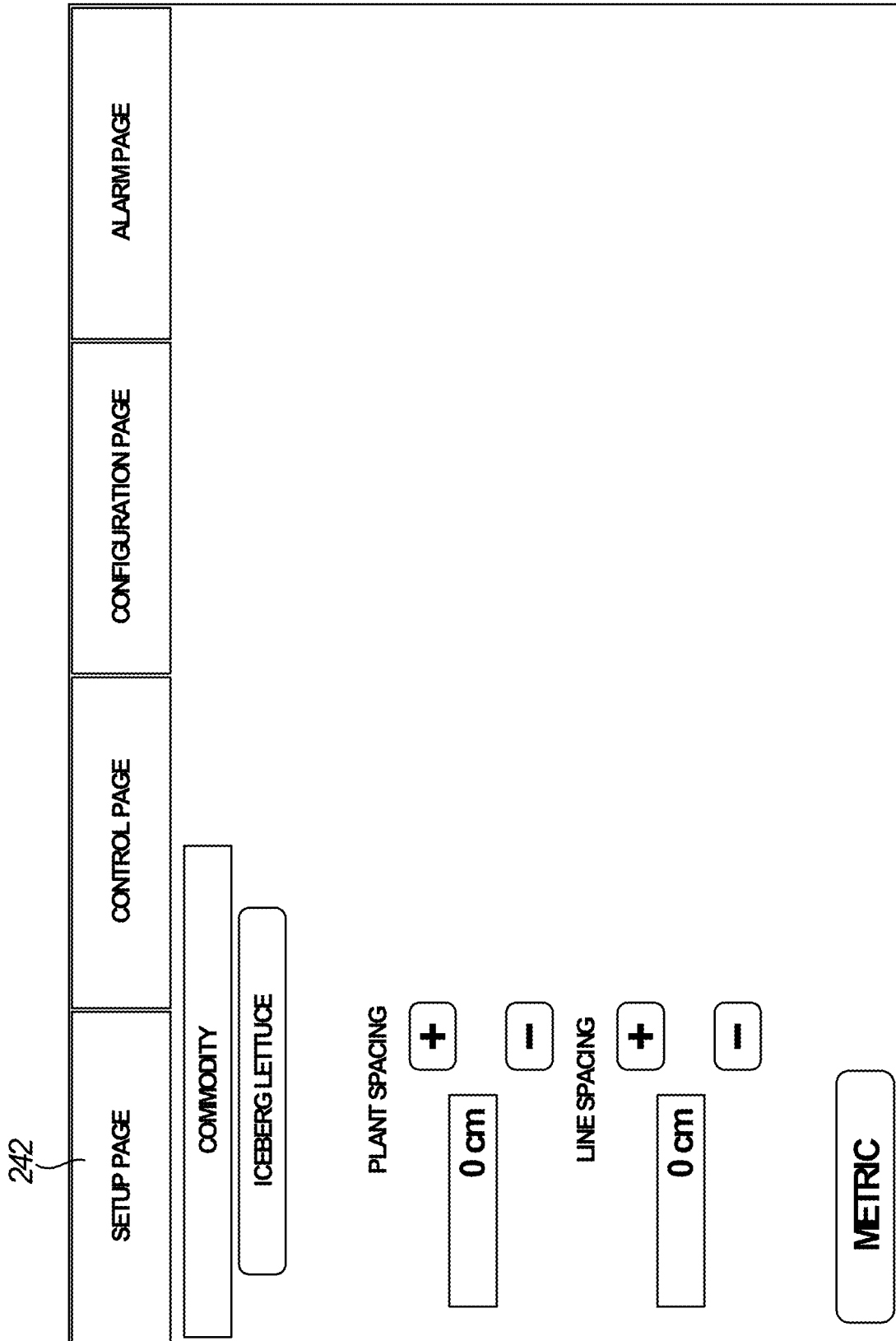


FIG. 9A



246

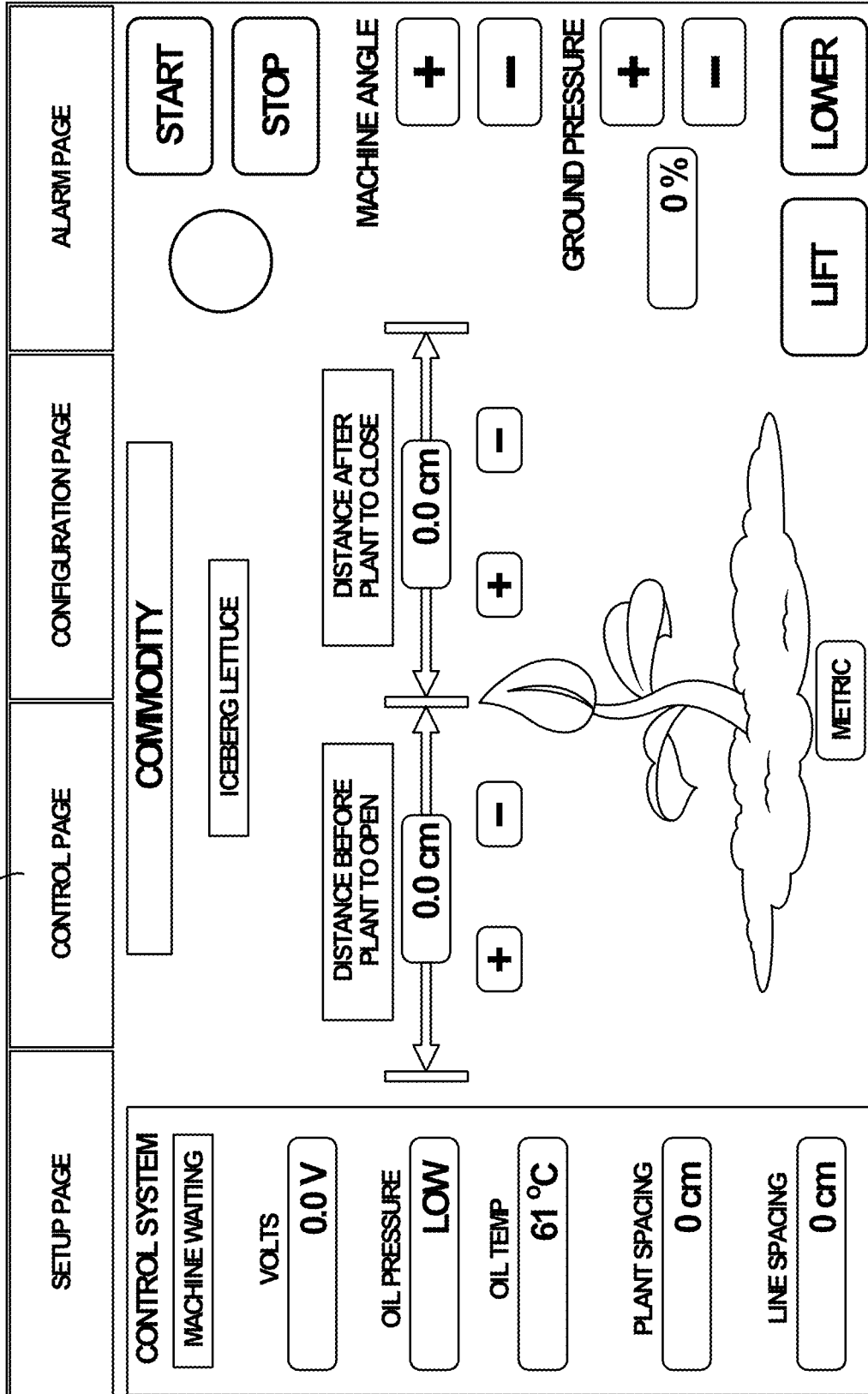


FIG. 9C

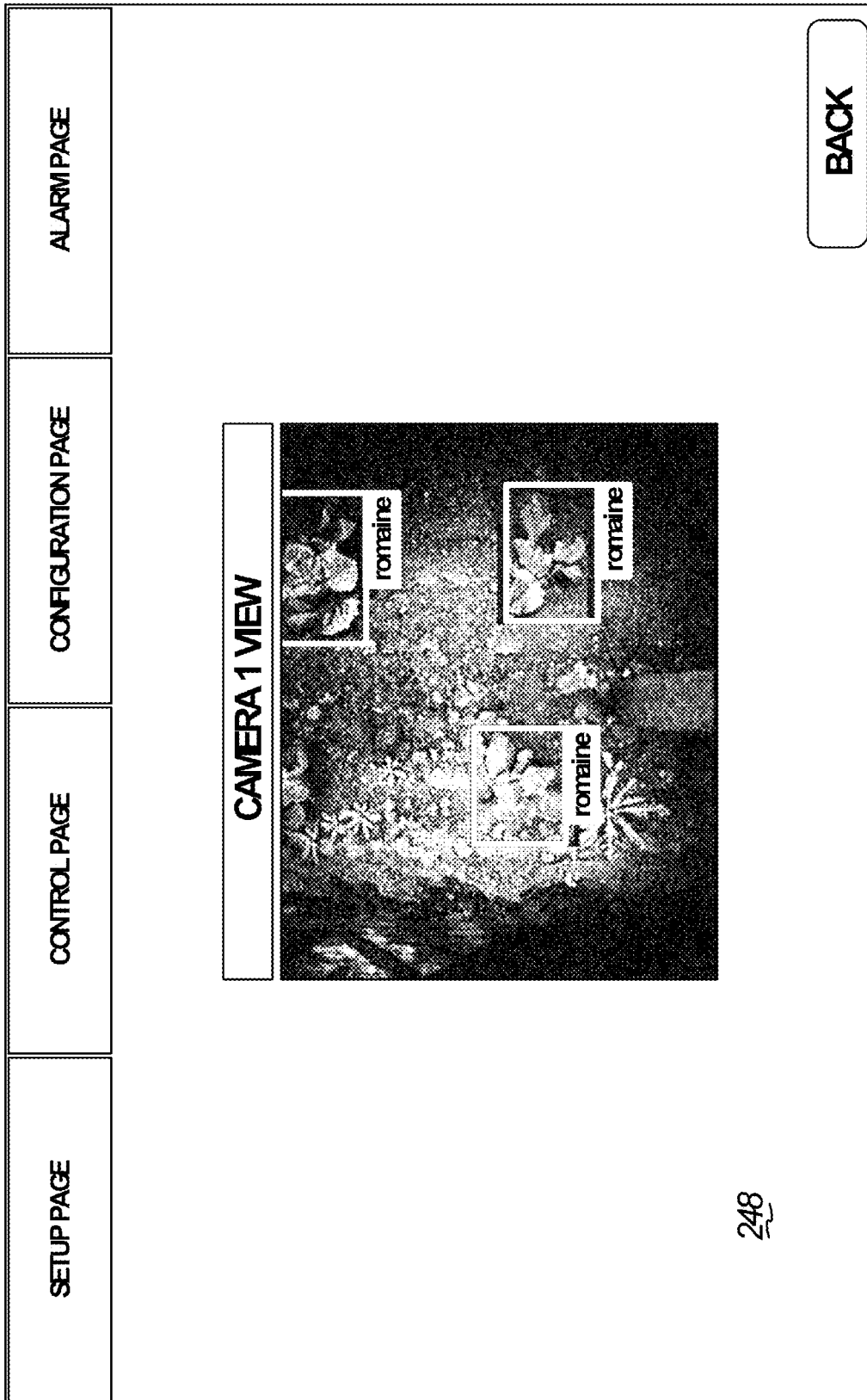


FIG. 9D

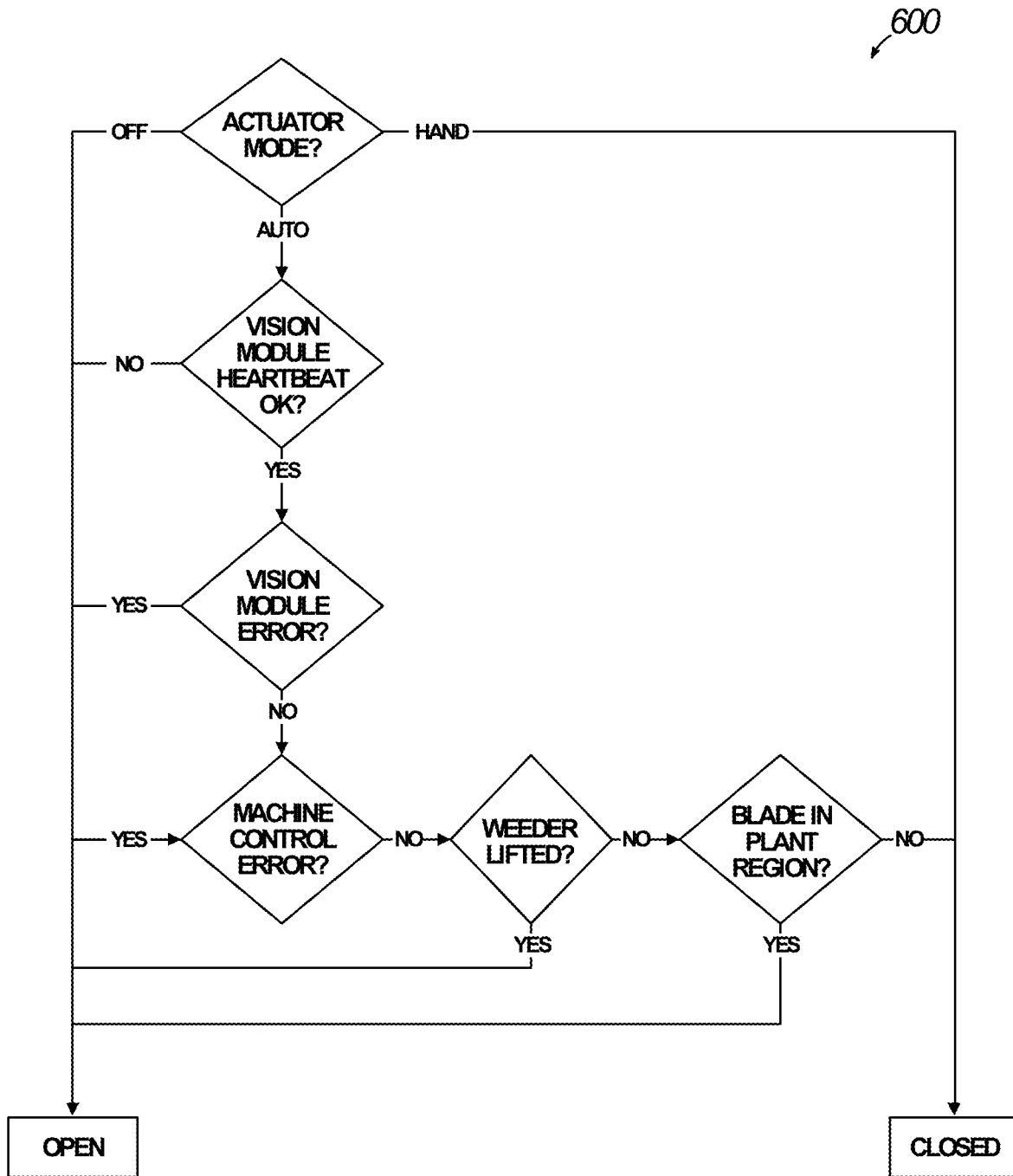


FIG. 10

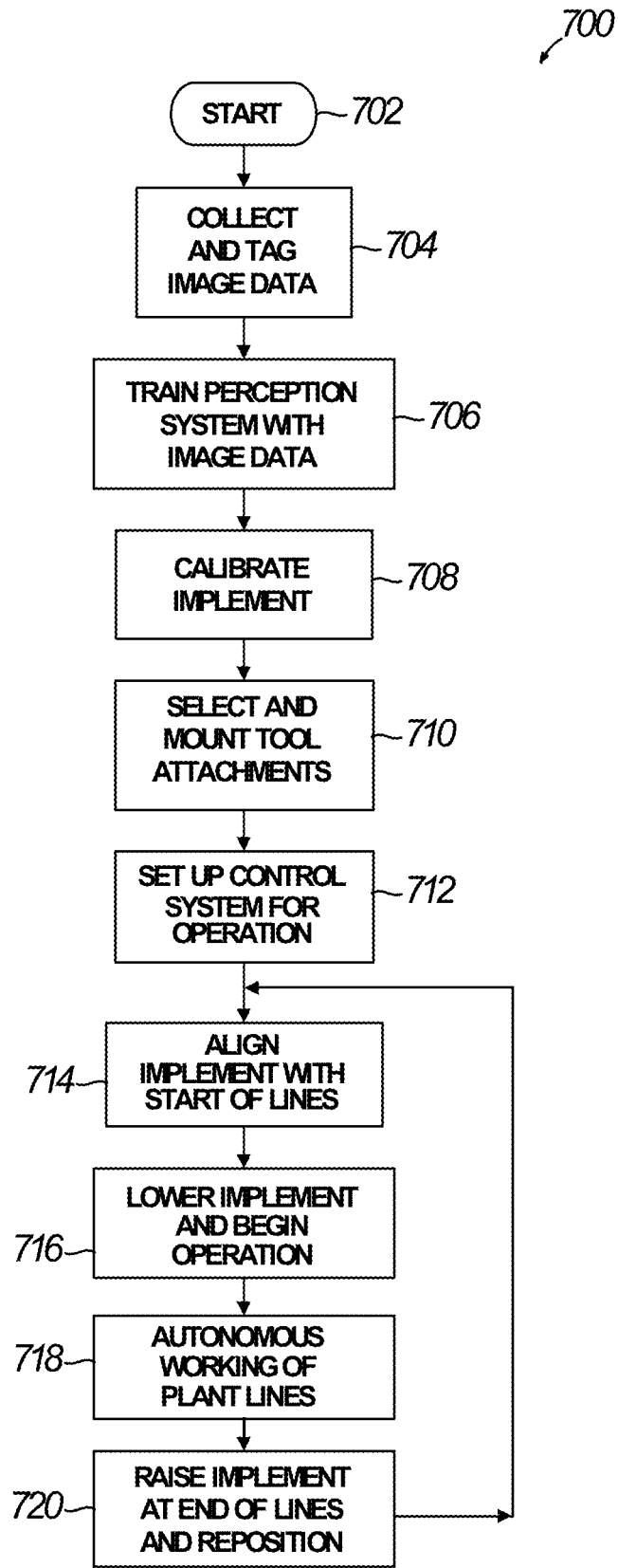


FIG. 11

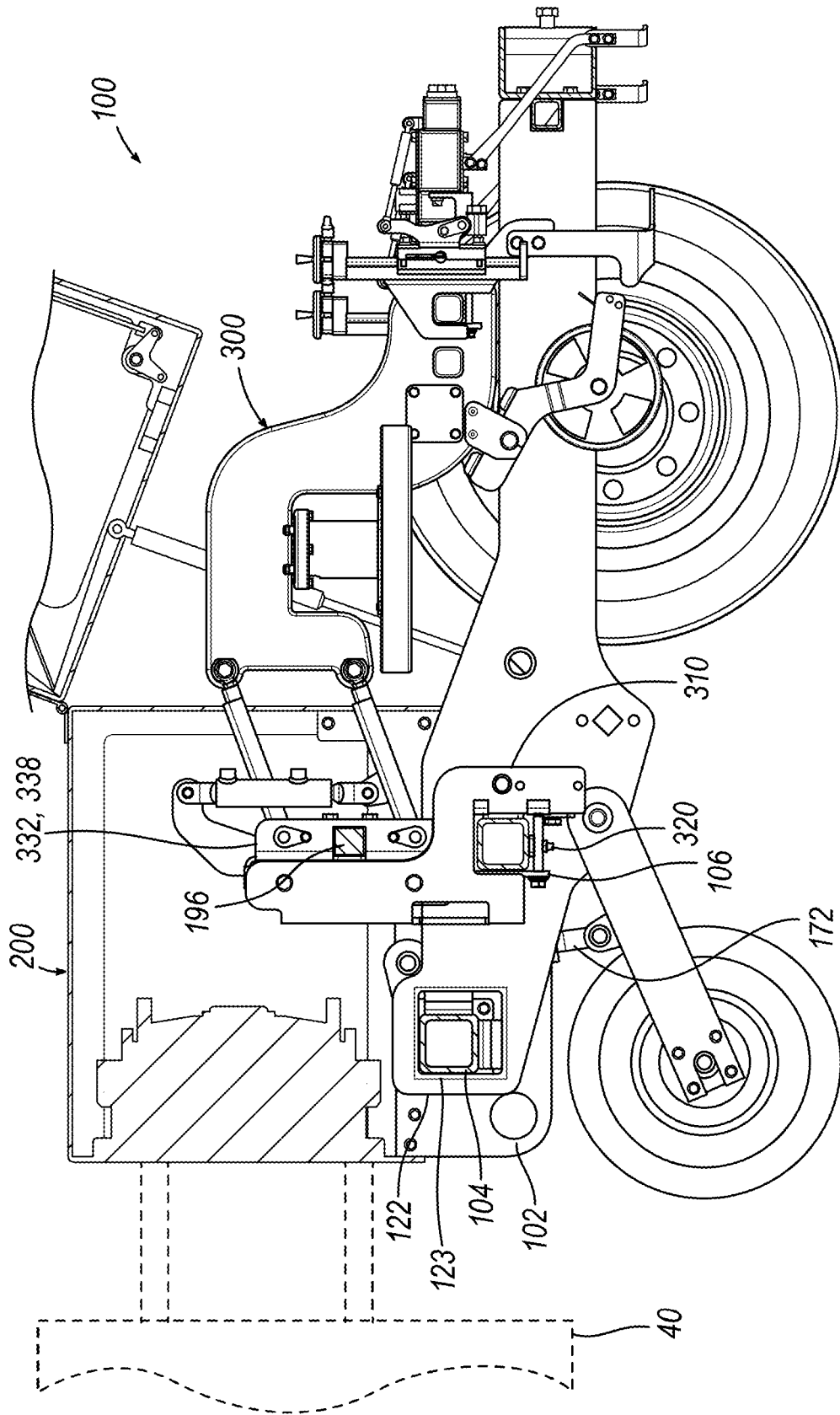


FIG. 12

# MACHINE VISION CONTROL SYSTEM FOR PRECISION AGRICULTURE

## CROSS-REFERENCE TO RELATED APPLICATION

This is a nonprovisional patent application of U.S. Provisional Patent Application No. 62/971,991, filed Feb. 9, 2020, and titled MODULAR PRECISION AGRICULTURE IMPLEMENT; U.S. Provisional Patent Application No. 62/972,641, filed Feb. 10, 2020, and titled MODULAR PRECISION AGRICULTURE IMPLEMENT; and U.S. Provisional Patent Application No. 63/074,544, filed Sep. 4, 2020, and titled MODULAR PRECISION AGRICULTURE IMPLEMENT; each of which are incorporated herein by reference.

## BACKGROUND

The present invention relates to automated machinery, and particularly, to a machine vision enabled control system for an agricultural implement.

## SUMMARY

The present invention may comprise one or more of the features recited in the attached claims, and/or one or more of the following features and combinations thereof.

An illustrative control system for an precision agricultural implement includes a controller having a convolutional neural network, a machine vision module, a plurality of sensors, and a plurality of actuators in communication with the controller, the plurality of actuators including a plurality of agricultural tool actuators.

Additional features of the disclosure will become apparent to those skilled in the art upon consideration of the following detailed description of the illustrative embodiment.

## BRIEF DESCRIPTION OF THE DRAWINGS

The detailed description particularly refers to the accompanying Figs. in which:

FIG. 1 is a schematic block diagram of an electrical system **180** and control system **200** of the agricultural implement **100** of FIG. 12;

FIG. 2 illustrates commodity bed **52a** cultivated with prior art implements and commodity bed **52b** cultivated with the agricultural implement **100** of FIG. 12;

FIG. 3 shows an illustrative process of a portion of agricultural implement **100** of FIG. 12;

FIG. 4A is a cross-sectional top view of the agricultural implement **100** of FIG. 12 illustrated in a first state;

FIG. 4B is a cross-sectional top view of the agricultural implement **100** of FIG. 12 illustrated in a second state;

FIG. 5 is an elevational view of a tool arm **300** of the agricultural implement **100** of FIG. 12;

FIG. 6 is an end side perspective view of the tool arm **300** of FIG. 5;

FIG. 7 is a side cross-sectional view of a vision module **500** of the tool arm **300** of FIG. 5;

FIGS. 8A and 8B are a schematic diagram of a hydraulic system **150** of the agricultural implement **100** of FIG. 12;

FIGS. 9A-9D are illustrative screen display plans from HMI **204** of control system **200**;

FIG. 10 is an illustrative state machine for actuation of tools **410**; and

FIG. 11 is an illustrative process of training and operating the agricultural implement of FIG. 12 for a commodity plant field operation; and

FIG. 12 is a cross-sectional elevational view of an agricultural implement **100** according to the present invention, taken along the section lines illustrated in FIG. 4A;

## DESCRIPTION OF THE ILLUSTRATIVE EMBODIMENTS

For the purposes of promoting and understanding the principals of the invention, reference will now be made to one or more illustrative embodiments illustrated in the drawings and specific language will be used to describe the same.

Referring to FIG. 12, a cross-sectional elevational view, and FIG. 4A, a cross-sectional top view, an illustrative embodiment of modular precision agricultural implement **100** is shown. Implement **100** includes generally a chassis **102**, control system **200**, and modular smart tool arms **300**. For clarity, FIG. 5 illustrates a modular smart tool arm **300** separated from the chassis **102**, and FIG. 12 illustrate a chassis **102** without any tool arms **300** attached.

Referring again to FIG. 4A, the illustrated implement **100** includes three tool arms **300**, each of which include at least one agricultural tools for working a crop and/or field, for example, a pair of tool attachments **400**. However, in other embodiments (not shown) fewer than three or more than three tool arms may be used with implement **100**. Each of the tool attachments **400** includes a pair of actuating tools **410**, in this example hoes used for cultivating. In FIG. 4A, the tools **410** are shown in an open position; however, upon actuation, each pair of tools **410** travel together, closing the space there between. In alternative embodiments of tool attachment **400**, aspects of the tool attachment and the control system **200** (computing and select other components of which may also be referred to collectively as 'controller' herein) may be adapted to providing intelligent tasks other than cultivation, for example, thinning, selective spraying, data collection, and possibly even planting and harvesting. Selective spraying can include actuation and/or controlled movement of to direct delivery from nozzles or other delivery devices to apply wet or dry chemicals to commodity plants **60** or weeds **70**, selected varieties of each, or both. Advantageously, chassis **102** and tool arms **300** can be used thereby used with a number of different modular and releasably attachable precision tool attachments **400** in addition to the illustrative tool attachment **400** disclosed herein.

Advantageously, chassis **102** can be propelled across commodity field **50** using standard farm equipment, for example a tractor having a suitable power takeoff (PTO) drive shaft and a hitch (not shown) to pull and operate chassis **102**. As will be discussed further below, the hydraulic system **150** and electric system **180** can both be powered by hydraulic pump **152** driven by the tractor PTO.

To understand an illustrative application of the illustrative implement **100** equipped with tool attachments **400** configured as a cultivator, refer now to FIGS. 2 and 3. Referring first to FIG. 2, commodity field **50** includes raised beds **52a** and **52b**, each bounded along the sides and separated by furrows **56**. An illustrative western specialty row crop, for example, romaine lettuce, is illustrated as commodity plant **60**. Bed **52a** is illustrative of cultivating to remove weeds **70** using traditional cultivator implements. Specifically, while weeds **70** grow within plant lines **62** in the spaces **74** between the commodity plants **60** and in the spaces **72** between plants lines **62**, traditional cultivating only reaches

and cuts or otherwise disrupts weeds **70** located in the spaces **72** between the plant lines **62**. The reason for this is that with traditional cultivators, the cultivating blades or other tools are static fixed devices which would destroy commodity plants **60** along with the weeds **70**, if employed along the plant lines **62**. This limitation has traditionally been addressed by using laborers to walk the beds **52a** and manually remove the remaining weeds **70** located within spaces **74** between commodity plants **60** of plant lines **62** with a hand hoe.

As illustrated in bed **52b** of FIG. 2, the illustrated implement **100** equipped with tool attachments **400** configured as a cultivator can be used advantageously to weed both the space **72** between plant lines **62** and the space **74** between commodity plants **60** within a plant line **62**, also commonly referred to as a planting interval for a row or crop row.

FIG. 3 illustrates a portion of the process and features providing this advantage and overcoming the limitation of requiring manual hoeing to effectively cultivate commodity field **50**. Referring to step **1** of FIG. 3, as implement **100** is operated along plant lines **62** of commodity field **50b**, a control system **200**, including a vision module **500** and perception system **270**, classifies and locates each commodity plant **60** along each plant line **62**. By determining the center point location and/or bounds of each commodity plant **60** the blades **414** of cultivator tool **410** can be actuated to avoid damaging commodity plant **60**. For example, as shown in step **2**, as blades **414** approach each commodity plant **60** along plant lines **62**, cultivator tool attachment **400** then actuates cultivator tool **410** to extend the space between blades **414**, as shown in step **3**, thereby avoiding cutting or otherwise damaging the commodity plant **60**. Referring to step **4**, by determining a location of the center point and/or the bounds of each commodity plant, for example, the location of the root structure of the commodity plant at the depth of the blades **414**, as the blades **414** of the cultivator tool **410** pass beyond each commodity plant **60** along plant line **62**, cultivator tool attachment **400** is actuated again, this time to close the space between blades **414**, thereby again acting to remove the weeds **70** between commodity plants **60** within the line **62**, for example, as shown in step **5**.

The above listed and additional features of the illustrative implement **100** will now be disclosed in further detail, and details of control system **200** will be disclosed further below.

Referring to FIG. 12, a chassis **102** provides a universal, smart, modular implement platform for a variety of precision agricultural implement applications. Chassis **102** generally includes a frame **110**, wheel assemblies **120**, a hitch receiver **140**, a hydraulic system **150**, and an electrical system **180**. Frame **110** can include a front crossbar **104**, a rear crossbar or toolbar **106**, and end plates **108**. Additional features of chassis **102** that also support the mounting and operation of smart tool arm **300** along with toolbar **106** include plant line alignment bar **196**, and threaded rod or screw **198**, all of which will be discussed further below. A key distinction in the function of toolbar **106**, plant line alignment bar **196**, and screw **198** is that the toolbar **106** alone supports the weight of the smart tool arms **300**, while the screw **198** and the plant line alignment bar **196** respectively merely adjust the position of and move a portion of each of the tool arms **300** along the x-axis **90**.

The illustrative wheel assemblies **120** are modular and can be slidingly mounted along and then secured in a desired position upon crossbars **104** and **106**. The front axle **128** supporting the gauge wheel **130** is further supported by cantilever **132**, which is pivotably attached at pivot **134** to the supporting brackets **122**. Advantageously, hydraulic cyl-

inder **172** couples between frame **110** and cantilever **132** to adjust the height of gauge wheel **130** relative to frame **110**, thereby changing the pitch of the chassis **102** about a longitudinal x-axis **90**. The pitch of the chassis **102** is controlled in order to set the pitch angle of blade **414** of tools **410** that will be further disclosed below. For cultivating, it is expected that the blades **414** will be preferred to be flat or to be slightly negative so that the leading edge of blade **414** is lower than the trailing edge of blade **414** to sever and displace the portion of weed **70** above the cut on its root.

An illustrative hitch receiver **140** coupled to crossbar **104** can be used to pull chassis **102** with a three-point hitch as is typically found on farm tractors. The hitch receiver includes lower devices **142** and an upper clevis **146**; however, other attachment and hitching systems could be used.

Referring briefly to a schematic of hydraulic system **150** illustrated in FIGS. 8A and 8B, the hydraulic system includes generally a power take off (PTO) driven hydraulic pump **152** to power from a tractor pulling the implement **100** the hydraulic system of chassis **102**, hydraulic motor **154**, reservoir **156**, hydraulic oil cooler **158**, distribution manifold **160a/b**, accumulator **162**, and main regulator **164**. Hydraulic motor **154** is driven by the hydraulic oil pressure provided by pump **152**. Hydraulic motor **154** in turn drives, for example using a flexible belt, an electrical generator, for example, an alternator **182**. Alternator **182**, for example an automotive type electric alternator, provides DC electric power for electric system **180**. Additional controls and actuators of hydraulic system **150** will be described below in further describing other aspects of implement **100**.

Electrical system **180** of chassis **102** can be alternatively powered by alternator **182** or battery **186**. Additionally, alternator **182** is capable of charging battery **186**. Electrical system **180** includes a power distribution and regulation module **184** (FIG. 1) that can provide regulated voltage, for example 12 V DC and 24 V DC, and voltage and current transient protection. Electrical system **180** can also power thermostatically controlled hydraulic oil cooler fans **188** and control system **200**, which will be described further below.

Additional features of chassis **102** will be discussed further below, following a discussion of the modular smart tool arms **300** that can be supported and operated by chassis **102**, for example, as is generally shown in FIGS. 12 and 4A.

Referring first to FIGS. 4A and 5, for numerous decades, a toolbar, for example toolbar **106** apart from implement **100**, has been the common point of attachment for agricultural tools to configure an implement for particular tasks and for particular commodity fields **50**, whether it be for plowing, disking, planting, cultivating, spraying, harvesting, or chopping. In contrast, according to the present disclosure, the function of prior agricultural toolbars can be provided and further improved upon by the illustrative tool arm **300** and the tool platform **370** (FIG. 6) provided therewith. Advantageously, various tool attachments, for example, the illustrative tool attachments **400** shown in FIG. 6, can be releasably mounted to and operated by tool arm **300** at tool platform **370**. Various aspects of chassis **102**, control system **200**, and tool arm **300** provide for modular, repeatable, precision in the configuration and intelligent operation of tool attachments **400**.

The tool arm **300** is modular in part in that it includes a mounting structure, for example, mount **310** which enables one or more tool arms to be releasably secured to toolbar **106** of chassis **102**, for example, as shown in FIGS. 12 and 4A. The tool arm **300** is also modular in part because of the tool platform **370** and tool attachment **400** modularity introduced briefly above and discussed more specifically further below.

Tool arm **300** is smart (intelligent) in part because it can optionally include a vision module **500** (FIG. 5), enabling intelligent automated operation of tool attachments **400** and optional data collection regarding commodity fields **50**, both of which will be discussed further below.

An important aspect of the precision of tool arm **300** is the design and manufacture of a unitary or monolithic member for releasably mounting agricultural tools to, for example, a backbone **350**. In the illustrative embodiment shown in FIG. 5, the backbone **350** is milled from a single aluminum billet, for example, approximately 1 to 1½ inch thick, which limits the weight of tool arm **300** while maintaining dimensional stability required for a modular precision agricultural functionality. Backbone **350** can include a number of precision mounting features **364**, including for example, the use of location and/or interference fit tolerances in milling and adding features such as receiving bores, threaded bores, locating pins, recesses, and the like. These or other precision features may include with any of linkage mounts **356** adjacent a base end **354**, tool mounts **360** adjacent tool end **358**, a vision module receiving area **362**, and a ground follower mount **366**. These features are in contrast to prior art devices providing a tool attachment platform that includes numerous members forming frames and other platforms that lack uniformity of precision between one platform to another and/or that lack dimensional stability and lack light weight that enables precise motion control and ground following of the crop and field operation working portion of the tool arm **300**.

As will be evident from the above and below discussions of the operation of implement **100** using control system **200**, it is particularly important to maintain precise displacements between the vision module **500**, the ground follower **390**, and the tool attachment **400**, which is why all three are modularly and precision mounted to a billet formed backbone **350**.

Referring to FIG. 6, tool arm mount **310** includes sides **312**, back span **314**, front span **316**, clamp **320**, and guides **322**. Sides **312** are rigidly connected with back span **314** and front span **316**. These components can be formed, for example, from ¼-¾ inch steel or other rigid material. Sides **312** define an opening **318** which is sized to receive toolbar **106** so that mount **310** may be secured thereon, for example, as shown in FIG. 12. As shown for FIG. 4A, the clamp **320** can be used to fixedly secure mount **310** onto toolbar **106**.

A system of adjustment left or right on toolbar **106** is included with the mount **310** and can be utilized before clamp **320** is secured to more easily move tool arm **300** into a desired position along the length of toolbar **106**. Referring to FIG. 6, sides **312** also define bores **324** that provide clearance for threaded rod **198** to pass therethrough. Advantageously, by locating a pair of sleeves **326** around threaded rod **198** and between sides **312**, and locating a threaded adjustment nut **328** between the sleeves **326**, small adjustments left and right to mount **310** along toolbar **106** can be made. For example, by holding one of adjustment nut **328** and coupling **199** from rotating, while at the same time rotating the other about threaded rod **198**, the mount **310** will shift left or right depending on the direction of rotation. For example, a coupling **199** is secured to the threaded rod **198**. If coupling **199** is held to prevent rotation while threaded adjustment nut **328** is rotated about the threaded rod **198**, the nut will translate left or right on the thread, thereby translating sleeves **326** and mount **310** left or right with it.

Referring again to FIG. 6, backbone **350** of tool arm **300** is coupled to mount **310** by articulating base **330**. Advantageously, articulating base **330** provides translation of back-

bone **350** along the x-axis **90** and the z-axis **94** relative to mount **310**. The x-axis **90** is the axis parallel to the longitudinal axis of toolbar **106**, and the z-axis **94** is the vertical axis perpendicular to the longitudinal axis of toolbar **106** and perpendicular to the working surface **58** of a commodity field **50**. The articulating base **330** includes generally a linear slide table **332**, linkages **342** and **344**, and a lift actuator, for example, a lift hydraulic cylinder **346** for vertically supporting and translating backbone **350** relative to the mount **310**.

Referring to FIG. 6, linear slide table **332** includes linear bearings **334** that translate along guides **322** of mount **310**. More specifically, guides **322** can be hardened cylindrical rods that provide a precision and wear resistant surface for linear bearings **334** to ride upon. This configuration advantageously allows backbone **350** and attached tool attachment **400** to translate smoothly and precisely along the x-axis **90** of chassis **102** particularly because movement of the excess mass that would be involved with translating toolbar **106**, mount **310**, and other additional structure such as frame **110** is avoided.

Still referring to FIG. 6, brackets **338** each define an opening **339** sized for receiving therethrough a plant line alignment bar **196**, as is shown in FIGS. 12 and 4A. Referring to FIG. 4A, advantageously, the linear slide tables **332** of each of the tool arms **300** mounted to chassis **102** can be each clamped to alignment bar **196** such that translation of the alignment bar **196** along its longitudinal axis, for example using hydraulic cylinder **176** actuated by side shift valve **178**, will simultaneously and equally shift the slide tables **332** and attached backbones **350** and tool attachments **400** of each of the tool arms **300**.

For example, referring to FIG. 4B and comparing it to FIG. 4A, in FIG. 4B the hydraulic cylinder **176** has been retracted, shifting plant line alignment bar **196** to the left and translating with it the articulating base **330**, backbone **350**, and tool attachment **400** portions of the tool arms **300**. The spacing of the tool arms **300** relative to each other remains precisely the same. Additionally, the large mass components such as mounts **310** of tool arm **300**, toolbar **106** and other portions of frame **110** and chassis **102** remain in place.

The movement of the least amount of mass as practical to precisely, smoothly, and quickly shift the tool attachments **400** left and right overcomes various disadvantages found in prior machines. For example, the actuation of hydraulic cylinder **176** left or right can be used to continually and precisely align tool attachments **400** with plant lines **62** of the commodity field **50** to account for shifts in plant lines **62** that occurred during planting and to account for shifts in the tractor pulling chassis **102**. Additionally, the control system **200** may include a side shift position sensor **238** (not shown), for example a switch indicating when plant line alignment bar **196** is centrally located, left of center, and right of center, or, alternatively, an absolute position encoder can be used, either of which facilitate closed loop control of the position of plant line alignment bar **196** and thus the position of tool attachments **400** in alignment with plant lines **62**.

Referring to FIG. 6, an illustrative four-bar linkage is formed in part by a bottom link **342** coupled between pivot **340** of bracket **338** and linkage mount **356** at base end **354** of backbone **350**. The four-bar linkage also includes top link **344** coupled between pivot **340** of bracket **338** and linkage mount **356** of backbone **350**. Cantilever **348** is coupled to the linear slide table **332** that brackets **338** are coupled to, and support an end of the lift hydraulic cylinder **346**, the opposite end of which is coupled to bottom link **342** approximately mid-span. As arranged, retraction of lift hydraulic

cylinder 346 translates backbone 350 and attached tool attachment 400 vertically upward along the z-axis 94 to a lifted or retracted position, as is shown in FIG. 6 and FIG. 12. In other embodiments (not shown) a different pivot and/or linkage structure can be substituted for the four-bar linkage 336 to provide movement through the z-axis 94 for tool arm 300.

The lifted position of tool arm 300 is useful to secure the tool attachments 400 attached to tool arm 300 up and away from the ground, for example, when implement 100 is transitioning between commodity fields 50 or between the end of set of plant lines 62 and the beginning of an adjacent set. Additionally, if operating in a field 50 with fewer plant lines 62 per bed 52 than the implement 100 provides, then one or more tool arms 300 can be selectively actuated to and locked, e.g., manually/hydraulically or via system hydraulic controls 210, in the lifted position so that only those required for the number of plant lines are lowered and used, advantageously, without have to physically remove tool arm 300 or components thereof from implement 100. The height of each tool arm 300 relative to the working surface 58 is set by the extension and retraction of hydraulic cylinders 346 for each tool arms 300 attached to chassis 102.

In one embodiment, the height is controlled by controlling the continuous hydraulic pressure applied to each end of the piston of lift hydraulic cylinder 346. In another embodiment, the height is controlled by controlling the continuous differential of the hydraulic pressure applied across the ends of the piston of the lift hydraulic cylinder 346. In yet another embodiment, discussed further below, the height is controlled by setting a continuous regulated hydraulic pressure to one end of the piston of the lift hydraulic cylinder 346, and by continuously controlling the hydraulic pressure applied to the other end of the piston of the lift hydraulic cylinder. For example, a proportional solenoid valve 170 (FIG. 8A) and analog pressure sensors (unnumbered, FIG. 8A) can be used as part of the control of the hydraulic pressure to control the height of the tool arms 300, as can feedback from a height sensor 398 of tool arms 300 above the working surface 58, as is discussed further below.

For example, upon reaching the end of plant lines 62, the hitch of the tractor pulling chassis 102 can be used to lift it up by hitch receiver 140. A lift sensor, for example, a pressure switch 218 (FIGS. 8A and 8B) associated with gauge wheel hydraulic cylinder 172 can detect that weight is off of the front axle 128 and activate a transit mode of control system 200, or a tilt sensor, accelerometer, ultrasonic sensor, or other motion, orientation, elevation, and distance sensor known in the art may be used. Upon the control system 200 detecting via pressure switch 218 that chassis 102 has been lifted, tool arm lift valves 170 can optionally actuate hydraulic cylinders 346 of the tools arms 300 to lift them to the raised position, thereby providing clearance between tools 410 and the ground. Additionally, if side shift position switch or encoder 238 detects the plant line alignment bar 196 is not mechanically centered, along with tool arms 300, then control system 200 actuates side shift valve 178 and side shift cylinder 176 to a reset position, for example, the alignment bar 196 and attached tool arms 300 are returned to mechanical center of the chassis 102 for the next operation. Additionally, control system 200 can deactivate the processing by vision module 500, perception system 270, and control of tool attachment 400 by ruggedized controller 202 until the chassis 102 has been lowered and weight is again detected on front axle 128 via pressure

switch 218, thereby pausing the working of a crop and/or field by an operation of the tool arms 300 at least until the chassis 102 is again lowered.

Returning to the discussion of tool arm 300, lift hydraulic cylinder 346 also can be controlled during operation to lighten the downward force toward the ground of tool arm 300 due to the weight of the various components of the tool arm. By applying hydraulic pressure to each actuation end of lift hydraulic cylinder 346, as introduced above, and individually controlling each of those pressures, thus also controlling the differential pressure, the amount of downward force operating on each tool arm 300 is very dynamically controllable, and responsiveness to following changes in the soil profile/level in the bed 52b for each of the individual tool arms 300, as will be discussed further below in the section further discussing the control system 200.

In a working or down position in which lift hydraulic cylinder 346 is at least partly extended (not shown) the various tool attachments 400 attached to the illustrative embodiment of the tool arm 300 are configured as a cultivator with a preferred operating depth of a short depth under the surface of the soil of bed 52. Referring now to FIGS. 5 and 9, the ground follower 390 of tool arm 300 helps maintain the vertical position of backbone 350 along the z-axis 94 such that the tool attachments 400 supported by the backbone 350 remain at a preferred depth or height relative to a working surface 58 of a field 50. In the illustrative embodiment shown in FIG. 5, ground follower 390 includes a lever 392 pivotably coupled at a proximal end to the backbone 350, extending downward at an angle from the backbone, and coupled to a distal end of the lever is a ski, wheel, and/or other member for contacting and following the working surface 58, for example, a roller 396 rotationally coupled to the lever 392. In the illustrative embodiment, the roller 396 does not support any weight of the tool arm 300 within a normal range of motion through which the lever 392 pivots as the height of backbone 350 above the working surface 58 varies; however, a stop 394, for example, an elastomeric bumper or the like, mounted between the lever 392 and tool arm 300 acts as a mechanical limit to provide a limit to downward reduction of height of the backbone 350 above the working surface 58, thereby limiting the range of downward movement of supported tool attachments 400 along the z-axis 94.

The illustrative embodiment also includes a height sensor 398, for example an angular encoder, for determining the relative height of the backbone and thus the working tools to the working surface 58. For example, the height in the illustrative embodiment is based on an lever pivot angle 399 of the lever 392 to the backbone 350, which changes as the mass of the lever 392 and roller 396 keeps the roller 396 in contact with the working surface 58 as a z-axis distance between the backbone 350 to the working surface 58 changes. In other embodiments the height sensor may be a ranging, accelerometer, or other sensor capable of determining the relative height of the backbone 350 or tool attachments 400 to the working surface 58.

The z-axis 94 location of the end of the various tool attachments 400 attached a tool arm 300 are generally set at a desired height below the bottom of roller 396 and ski 398 for the illustrative application of cultivation. By the control system 200 controlling the hydraulic pressure applied to a first port of the lift hydraulic cylinder 346 to provide upward lift to backbone 350, at least a portion of the weight/mass of and supported by the tool arm 300 is supported and the downward force of the roller 396 is reduced in order to prevent soil compaction and excess lowering of the tool arm,

while also maintain enough downward force and system responsiveness to follow the elevation of the soil surface of the bed 52 being worked.

For example, in an illustrative embodiment, a continuous regulated hydraulic pressure of 600 psi provided to a first port of lift hydraulic cylinder 346 that provides upward movement of the backbone 350, and a continuous regulated hydraulic pressure of 200 psi provided to a second port of lift hydraulic cylinder 346 that provides downward movement of the backbone 350, provides a desired 'float,' i.e. upward offset or relief of the weight of and supported by the tool bar 300, to provide responsive following of the working surface 58 by the ground follower 390 and thus the tool arm 300 and supported tool attachments 400, while also preventing excessive compaction of the working surface 58 by the ground follower 390, which would extend the working tools downward beyond a desired height relative to the working surface 58.

Furthermore, in the illustrative embodiment, the control system 200 receives data from one or more pressure sensors 222 for measuring the hydraulic pressure at the first and the second port, or the differential hydraulic pressure, along with receiving data from the height sensor 398, which together are used by the control system 200 to actively regulate one of the continuous differential hydraulic pressure between the first and second port, or the continuous regulated pressure applied to the first port, in order to maintain the tool arm 300 and supported tool attachments 400 at a desired height along the z-axis 96 relative to the working surface 58. In one embodiment, a proportional hydraulic valve 170 controlled by the control system 200 controls a continuous but variable hydraulic pressure to the first port, feedback of that pressure is provided by the pressure sensor 222, and the continuous regulated backside pressure to the second port is preset and not variably controlled. An advantage in responsiveness and precision in desired height of the tool arm 300 over a working surface 58 having varied conditions and varied elevation is provided over prior art designs by the combination of the continuous and regulated downward pressure supplied to the second port, and the continuous variably controlled upward pressure supplied to the first port of the lift hydraulic cylinder 346. In one illustrative embodiment, a separate proportional hydraulic valve 170 and pressure sensor 222 is used for each of the tool arms 300 and hydraulic cylinders 346. In one illustrative embodiment, the control system 200 incorporates a low pass filter to the height control data from the height sensor 398, and/or other damping to the control of the height of the tool arm 300. In another illustrative embodiment, the lever 392 is fixedly mounted to the backbone 350.

Referring now to FIGS. 6 and 7, a vision module 500 includes module housing 504 which can be precisely coupled to backbone 350 by mounting interface 502 and precision mounting features 364, for example precisely located threaded bores and/or locator pins, within a protected vision module receiving area 362. The vision module 500 also includes a pair of lamps 506 coupled to vision module housing 504 by lamp mounts 508. In the illustrative embodiment, the lamps 506 are of sufficient intensity to greatly reduce or eliminate the effects of sunlight and resulting shadows that may otherwise be experienced by vision module 500 and associated perception system 270.

In the illustrated embodiment, camera 510 and optics 516 are packaged with a cylindrical vision module housing 514 and optional module housing lens protector 522. Camera 510 is a high-speed digital camera and includes an electronics package 512 and connectors 514, providing high-speed

pixel level transmission of digital images to other portions of control system 200, for example to perception system 270 that will be further discussed below. Advantageously, camera 510 can be paired with an optical lens 516, sealed within the optical housing 520 and protected by dust protection lens 518. Determining the correlation for a particular optical lens 516 between the x-axis 90 and y-axis 92 fields of view and distances and the height of vision module 500 above the base of ground follower 390 enables mapping objects of interest from the images to a machine-relative coordinate space used by the control system 200. For example, a field of view of the working surface 58 in one axis equal to twice the focal distance provides a known basis for determining the relative distance between pixels in captured images by knowing the focal distance, which is maintained by the ground follower 390 remaining on and following the working surface 58 of the soil of bed 52b, and taking into account field of view distortion for each pixel, i.e., the optical distance of an object to the camera for a given pixel due to angular offset from the lens' optical/longitudinal axis, versus the linear distance along the working surface 58 of the bed 52.

For example, in the illustrated embodiment of tool arm 300, the displacement of the focal plane of optical lens 516 and camera 510 of the vision module 500 above the bottom of roller 396 and ski 398 is set to a fixed measurement of 18 inches, thus providing an 18 inch field of view across the entire x-axis 90 and also the y-axis 92 of the digital images captured and transmitted by camera 510. A different fixed height measurement and focal view sizes may be used for other cameras and lens combinations, or for tool arms 300 adapted for different functions or crops of taller heights.

The correlation of locations and distances within captured images is critical to determining the timing of when to open and close tools 510 to avoid a commodity plant 60 which has been identified in an image captured a known distance ahead of the tools 410. To improve the correlation of the location of the commodity plant with the actuation of tools 410, it has been found advantageous to take into account fixed, variable, and asynchronous processes relating to detecting and correlating a commodity plant with the machine-relative coordinate space. For example, applying an image timestamp upon the perception system 270 receiving the first data packet containing part of a new image from the vision module 500, and applying a timestamp to data from the odometer encoder 232 based on the midpoint time between the data request and the receipt of the data.

An example of the coordinate space and tracking of the location of objects of interest and the tools 510 in the coordinate space can be understood from steps 1 thru 5 of FIG. 3, which correlate to the change in relative location of the objects of interest, e.g. commodity plant 60 and weeds 70, and the tool blades 414 as the implement 100 traverses the plant line 62. Although shown in a simplified version with only one plant line 62 in a field of view versus two in the illustrative embodiment, each of the steps 1 thru 5 of FIG. 3 correlates to the x-axis 90 and y-axis 92 dimensions of the coordinate space, divided along each axis into a desired level of pixel or bin resolution that corresponding relates to the images and actual distances imaged and traversed.

Referring to FIG. 6, as shown on the left side of tool in 358 of backbone 350, tool arm 300 also includes a tool platform 370 for modular and releasable mounting of tool attachments 400. For example, a platform toolbar 372 may be precisely located on backbone 350 by a tool mount 360. The platform toolbar 372 can support a tool mount 374,

which may include precision locating features such as those discussed for backbone 350 for the precise mounting of tool attachment 400 thereto.

Referring to FIG. 6, optionally the tool platform 370 of tool arm 300 may include a device for adjusting or actuating tool attachment 400 relative to backbone 350, for example a z-axis linear slide table 380 as shown in the illustrative embodiment. One reason to include adjustment for each separate tool attachment is due to variations found in commodity fields 50 among different plant lines 62 within the same bed 52a. For example, depending on the formation and environmental conditions such as compaction and erosion of bed 52a, individual plant lines 62 may vary in height. For example, there may be a crest across the bed 52a such that plant lines on one part of the bed are at a lower elevation than plant lines on another part of the bed, which also may vary from the relative elevation of the furrows within which wheel assemblies 120 of the chassis 102 ride.

In the illustrative embodiment, the slide table 380 provides manual adjustment along the z-axis 94 relative to the backbone 350 of a tool attachment 400 mounted to the slide table. The slide table 380 includes linear guides 382 upon which a table 384 may be translated up and down, for example, by cranking adjustment handle 386 and then locking table 384 in the desired position using locking handle 388. The table 384 provides a precision mounting surface for tool attachment 400.

Referring now to FIG. 6, an illustrative tool attachment 400 can be modularly and precisely coupled to tool arms 300. Base 402 is coupled to the tool arm 300, for example, to tool platform 370 or optional z-axis linear slide table 380. A crop or field working tool actuator, for example, actuator 420 of tool attachment 400, can be a hydraulically driven actuator that includes housing 430 coupled to base 402.

In the illustrated example shown in FIG. 6, the tool arm 300 cultivates two adjacent plant lines 62; therefore, each tool arm 300 includes a pair of tool attachments 400, one for each plant line 62. The tool platforms 370 on the left and right side of backbone 350 are spaced along the x-axis 90 so that the distance between the two tool attachments 400 matches the distance between plant lines 62. Additionally, the illustrative tool arm 300 is equipped with static mounts 302 which have attached static cultivators 304, each positioned to cultivate and clear weeds located within the space 72 between plant lines 62.

As discussed earlier above, illustrative tool attachments 400 include tools 410 for cultivating the space 74 between adjacent commodity plants 60 within plant line 62. As illustrated in FIG. 4A, actuator 420 is in a normal and failsafe position in which arms 412 and blades 414 of cultivating tools 410 are spread apart a distance sufficient so that the blades traverse the open space 74 between plant lines 62, as illustrated in FIGS. 2 and 3 and do not contact the root or other portion of commodity plant 60. Upon actuation of tools 410 by actuator 420, shafts 466 extending through covers 432 of the housing 430, and upon which arms 412 are attached by mounting features 468, rotate in a synchronize fashion to translate blades 414 into close proximity, thereby cultivate the space 72 between the commodity plants 60 within the plant line 62.

The actuation of tools 410 provided by the actuator 420 is advantageous in that the movement of the tools 410 are synchronized and provide a transition time between the open and close positions that can be adjustable by an electronic solenoid controlled valve 426, for example, a proportional flow valve set by controller 202 and/or input at HMI 204, and/or a flow regulator 428 (not shown), located directly at

housing 430 in the illustrative embodiment to reduce latency and other undesirable characteristics with more remote activation. Additionally, actuator 420 provides a slow initial and final speed and ramping up and down from initial and final speed to the transition speed to avoid impulse like accelerations and decelerations, thereby greatly reducing or eliminating any harmonic induced or other vibrations of arms 412 and blades 414 and also greatly reducing or eliminating disturbance of soil that could damage the commodity plants 60, including from throwing soil onto the commodity plants, as with prior designs, which can inhibit growth and or induce spoilage.

A motion profile provides position sensitive damping, providing damping that prevents jerking of tools 410 near the limits of travel of the actuator, advantageously minimizing or eliminating the throwing of soils by tools 410, particularly soil that could be thrown onto the commodity plants. The motion profile can be provided solely by the hydro-mechanical features, solely by hydraulic valve controls, electro-mechanical features, or a combination of these.

Referring to FIG. 4A, in one illustrative embodiment of implement 100, a second and third set of tools arms 300 are provided by coupling toolbar extensions 107 to each end of the toolbar 106 of chassis 102. Advantageously, the frame 110, wheel assemblies 120, hydraulic system 150, electrical system 180, and control system 200 have all been sized to accommodate the added loads of three sets of on or more tool arms 300, thereby reducing the number of passes required to complete cultivation of a commodity field 50 by a factor of three.

Referring to FIG. 1, a schematic block diagram illustrates aspects of electrical system 180, including control system 200. Control system 200 can include a ruggedized controller 202, for example, an X90 mobile controller available from B&R Industrial Automation of Roswell, Ga., and a machine vision/perception computer 270, including a graphics processor (GPU) 272 such as a TX2i available from NVIDIA Corp. of Santa Clara, Calif. Controller 202 provides overall machine control of implement 100, and perception computer 270 includes processing of images received from vision module 500, including a neural network, for example, a convolutional neural network (CNN) for AI processing of images and optionally other data to classify, locate, and bound objects of interest, including at least commodity plants 60, and optionally other objects, including for example, weeds 70 and debris (not shown), and to provide a confidence level associated with the classification and/or bounding. Classification of objects of interest may include the plant or weed variety, health, for example, including a disease state/type, and other attributes in the art that are knowable optically. Alternatively, a single computing unit may be substituted and provide the machine control, image, and AI processing. Also alternatively, some or all of the functions provided by one or both of the machine controller 202 and perception computer 270 may be provided by the vision module 500. The perception computer 270 may also include pre-processing of images prior to processing by the CNN, and/or post-processing of data resulting from the CNN processing of images.

In some implementations or selected use of implement 100, control of the tool attachment 400 may only require processing of objects classified as the commodity plant of interest, in other implementations or selected use, control may only require processing of objects classified as weeds or a set of weed types, and in yet another implementation or selected use, control may require processing of both commodity plants and weeds. For example, depending on

whether the attached tool attachment **400** is being used for weeding, thinning, or application of chemicals, including selectively on one or both of commodity plants and weeds.

Control system **200** also includes various controls **230**, generally interfaced with controller **202**, for example via a wireless or wired local area network (LAN) **206**, for example, Ethernet. Controls **230** may include HMI **204**, for example a touchscreen display device, and various input sensors, including a tilt sensor/inclinometer **234**, odometer encoder **236** mounted with axle **124** (FIG. 12), side shift position switch or encoder **238**, and various hydraulic pressure sensors **212-222**. Control system **200** also includes output controls, generally controlled by controller **202**, including valves controlling hydraulic actuators, including cylinders, discussed above. Machine controller **202** thus generally controls actuator **420** to close and open cultivator tools **410** around commodity plants **60**, side shift of tool arms **300** to maintain alignment of the tool attachments **400** with plant lines **60**, pitch control of blades **414** via control of gauge wheels height, controlling the height of tool arms **300** to maintain proper blade depth **414**, and to lift and/or center tools arms **300** in a transit mode when raising of implement **100** is detected.

Perception computer **270** provides the image processing, including bounding, classification, confidence, and location mapping of objects of interest, including commodity plants **60**, to implement the general process illustrated by FIG. 4 and discussed further above, including providing the data necessary for some of the processes controlled by controller **202**, including the closing and opening of the cultivator tools **410** around commodity plants **60**, and side shifting of the tool arms **300** to maintain alignment of the tool attachments **400** with plant lines **60**. To do this, perception computer **270** provides generally AI enabled object detection, and maps the detected objects to a relative coordinate space derived from timestamping of displacement data from the odometer encoder **236**, image timestamping, and determination of objects of interest, including the centerline of plant lines **62** relative to vision module **500**, and thus relative to the tool attachments **400**.

Advantageously, the operation of implement **100** is not dependent on GPS or other such absolute or geographic positioning data or systems and can function solely using the relative positions of the plant lines **62** and the commodity plants **60** detected by the perception computer **270**. Advantageously, the operation of the control system **200**, including perception computer **270** and controller **202**, may be autonomous in that it does not require remote data or computer resources; however, a local or remote wireless or wide area network (WAN) connection **208** may be used to remotely monitor, update, or to optionally supplement the data and computing resources of the control system **200**.

Referring to FIG. 9A, an illustrative HMI layout for a setup page **242** is illustrate. For example, the setup of control system **200** can include selecting a commodity plant type, a unit of measurement, and the spacing between commodity plants **62** with the plant line **60** and the spacing between adjacent plant lines **60**.

Referring to FIG. 9B, an illustrative HMI layout for a configuration page **244** includes entering the distance from the blades **414** of each tool attachment **400** to the center of field of view of the camera module **500** on that tool arm **300**. Other configuration relating to the tool attachment **400** can include timing information relating to the cycling of the blades **414** through their range of motion. Other configuration information includes cooling fan **118** temperature trigger, pressure limit settings and delay and transition times for

the actuation up and down for the tool arms **300**, odometer **336** calibration for rear wheel **126**, ground pressure backside and wheels threshold.

Referring to FIG. 9C, an illustrative HMI layout for an control page **246** is illustrated. Information displayed includes the overall status of control system **200**, voltage of electrical system **180**, hydraulic oil pressure and temperature, and settings selected on setup page **242**. Additional control settings that can be selected include the distance prior to plant center to open tool **410**, the distance after plant center to close tool **410**, machine angle, which sets the pitch of blades **414**, and a percent of ground pressure, which relates to how much the tool arm **300** lift hydraulic cylinder **346** lightens the weight of the tool arm **300** applied to the ground by ground follower **390**. And finally, a system start/stop selection and a tool arm lift/lower selection is provided.

As illustrated by FIG. 9D, the HMI **204** also provides a selectable real-time view from each vision module **500** and an alarm page.

Advantageously each vision module **500**, which in the illustrative embodiment includes one camera **510**, is centered between two plant lines **60** and has a sufficient field of view for typical spacing between plant lines **60** in beds **52b** to have within its field of view and process the classification, confidence, location, and/or bounds for up to at least two plant lines **60** simultaneously. Tracking two plant lines **60** by a single camera and image not only reduces hardware requirements, but also provides for more precise plant line following than is provided by one camera centered on and tracking each plant line. Additionally, for embodiments that limit each camera **510** to tracking two plant lines, instead of tracking all plant lines **60** in a bed **52b**, better resolution, precision, and data collection is provided by the vision module **50**.

Lamps **506** are strobed at an intensity near sunlight levels to minimize the impact of variations in sunlight and on shadows that dependent on environmental conditions and time of day. The set of images and data to train the CNN used with perception computer **270** can nonetheless include images taken in various environmental conditions and times to day to improve functionality.

In the operate mode, the processing and control timing accommodates a rate of travel of implement **100** up to a limit, for example, a limit that ensures every commodity plant **62** will appear in at least two images before that plant will be out of the field of view of the camera **510** and approaching the tools **410**. Using such a limit improves classification, locating, and tracking and is also required to ensure tools **410** can be actuated and the blades **414** translate to an opened position opened before the arrival of the plant **62** at the blades **414**. Alternative or additional criteria for rate of travel may also be used, including commodity plant or environmental conditions warranting a lower rate than the implement **100** may be technically capable off.

An illustrative state machine for actuation of tools **410** is shown in FIG. 10.

Pre-processing of image data by vision module **500** or perception computer **270** prior to inference processing by the CNN or other AI model can include, but is not limited to, image timestamping, converting the image color space, for example, to RGB, rotating, rescaling the image, and other pre-processing known in the art.

Additionally, post-processing of the object bounds, location, classification, and confidence provided by the CNN or other AI model can be used to reduce errors and provide some fail safes for the AI processed data. For example, when

the operation mode is initiated at the beginning of a plant line **62**, the tools **410** remain open until commodity plants have been classified and located for a preset span of distance along plant line **62**. Also, since the root of a commodity plant **60** is what is being protected for weeding, by actuating the tool **410** to separate the blades **414**, post-processing determines the center of the bounded object, thus more precisely locating the root and allowing closer weeding to it. Additionally, detected objects with a confidence level below a selected threshold may be ignored or reclassified, as can objects with a bounding size outside of a threshold range.

Also, threshold ranges can be statically selected, or may be dynamically selected or dynamically adjusted based on average, mean, or other data analysis of object detections for a particular bed **52**, field **50**, type of commodity plant **60**, period of time, or other such adjustment set criteria. For example, commodity plant **60** intervals or bounding size may be dynamic. If commodity plants **60** have been consistently classified and located at a regular interval of distance, if an expected commodity plant **60** is not identified along the plant line **62** at the expected interval, the existence of a commodity plant **60** at that location can optionally be inferred to avoid removing a commodity plant **60** that was not identified by the perception computer **270**. Inversely, a potential false positive can be inferred and optionally reclassified for removal, for example, if a commodity plant **60** is classified and located at a location between the regular interval, additionally or alternatively, an outlier from a consistent range of bounding sizes may optionally be inferred to be a false positive.

If the distance between the location of two adjacent commodity plants **60** along a line **62** is too small and is thus insufficient to reliably cycle the tools **410** closed and opened again before the tools **410** traverse the second commodity plant, optionally the objects may be merged and the tools **410** will remain open for the full span of the two commodity plants **60**, or non-max suppression may be used to remove the object with a lower confidence level, bounded size, or another such parameter. Additionally, or alternatively, commodity plants **60** located at other than the expected interval may be reclassified or otherwise treated as a weed for removal by tools **410** if thinning of the commodity plants **60** is desired and selected. Commodity plants **60** that are not located within a threshold range of a plant line **62** may also be reclassified or otherwise treated as a weed.

Also, if the inference time is not sufficient to classify and locate commodity plants in time for the tools **410** to be opened, for example, if the implement **100** is being pulled at too high of a speed, the tools **410** will remain open to prevent damage to the plant line **62**.

Lastly, pre- and/or post-processing also addresses plant line **62** following and the left-right centering of the tools **410** on each plant line. For example, in the illustrative embodiment a single vision module **500** is used for two adjacent lines **62**. Depending on the field of view **58** of the lens **516**, objects detected in lines **62** to the right and left of the two lines being worked by the that tool arm **300** may be masked in pre- or post-processing. Also, if a single line **62** is detected for one of the vision modules **500** rather than a pair of lines, rather than post-processing centering the left-right shifting of the tools arms **300** between the two lines, they are offset from the single line the appropriate distance for the line spacing set, for example, via the HMI. Also, left-right shifting may be based on a single selected vision module **500**, or based on an averaging or other post-processing data analysis of the relative line locations detected for some or all of the vision modules **500**.

For commodity plants **60** and optionally other objects that are classified and for which a location, bounding, and confidence level is desired, the image timestamp is matched to data from the odometer **232** for that timestamp, or, to save communication and computing bandwidth for the odometer, odometer data can be interpolated from the odometer data spanning the image timestamp. The odometer location of the plant can be determined from the timestamp, for example, by offsetting the odometer location based on the conversion from pixels that the plant is from the center of the field of view of the image. Finally, the odometer data increment at which the plant will be located at the location of blades **414** can then be determined by knowing the odometer distance between the center of the field of view of the image and thus camera **510** and the blades **414**.

Alternatively, the location mapping of the commodity plants **60** can be done based on odometer and pixel conversions to real world measurement coordinate space, or to a different, even arbitrary measurement and location base for a coordinate space, as long as it correlates to the real world location of the camera **510**, blades **414**, and plants **60**. Additionally, image flow of objects between consecutive images can be processed by perception computer **270** to determine speed and relative distances/locations over time, including when plants **60** will be located at blades **414** without requiring the use of data from an odometer **236**.

An illustrative state machine **600** for reliable actuation of tools **410**, including the above discussed features, is shown in FIG. **10**.

FIG. **11** is an illustrative process **700** for training and operating implement **100** for a particular operation on a field of a particular type of commodity plant **60**. Generally, the first three steps are completed by the implement builder, supplier, and/or service provider, and the remaining steps **704** through **708** are completed by an end user. In step **704** one or more sets of image data relevant to a particular type of commodity plant **60** are collected and objects in the image are tagged, for example objects are tagged as commodity plant, weeds, and/or other objects, including typical debris such as rocks and dead vegetation. Generally the image data will be most effective at training perception system **270** for an acceptably high rate of performance if the image data is collected using the vision module **500** and under all environmental and other conditions expected to be experienced in operation, including variations in soil, soil condition, maturity of or absence of commodity plants and weeds, and the like as is known in the art. In step **706** the perception system **270** is trained using the image data. This step may involve multiple sets of data, training and testing, varying the selected neural network model, varying parameters of the selected neural network model, and/or otherwise tuning the performance of the model as is known in the art of machine learning.

In step **708**, the implement is calibrated. For example, various system and subsystem hydraulic pressures of hydraulic system **150** are set with manual regulators and/or the HMI touchscreen **204** as discussed above, any input sensors requiring calibration are calibrated, for example, setting the odometer encoder **232** based on the rear wheel **126** diameter. Additionally, the portion of the hydraulic system **150** operating the lift hydraulic cylinder **346** for the four-bar linkage portion of the tool arm **300** is calibrated to operate within a selected range of differential pressure and individual pressure limits to provide an operator selectability within that range. For example, so that the operator can easily adjust within the preselected range the weight of the tool arm **300** that is carried by the lift hydraulic cylinder **346**

versus any weight on the ground applied by the ground follower **390** or the tool **410**, depending on desired operation, performance, and characteristics, including but not limited to a desired level of dynamic following of varied soil profile levels, current field conditions, and soil compaction presence and/or avoidance. If the specific tool attachment **400** is mounted to tool arm **300**, then the distance from the end effector of the tool, for example, blade **414** to the center of the field of view of vision module **500** is also measured or otherwise verified and set in control system **200**. Other additional calibration and or testing may also be completed at this step.

Still referring to FIG. **11**, in step **710** an operator selects and mounts the tool attachment **400** for the desired operation and the particular commodity plant type. Advantageously, the same chassis **102** and the same tool arm **300** can be used for a wide range of commodity plant types and a wide range of operations. Training may need to be completed for control system **200** to handle some variations in plant types and operations, and different tool attachments **400** may also be utilized.

Once the tool attachments **400** are mounted to tool arms **300**, in step **712** the operator can next provide any desired setting for control system **200** at HMI **204** for that specific operation, including as illustrated in FIGS. **9A-9C** and discussed above, and also any additional calibration from step **708** which can now be completed with the mounted tool attachments **400**.

In step **714**, a vehicle such as a tractor **40** is used to power and navigate the implement **100** to and within a field **50** to be worked. The implement **100** is lined up with the start of the commodity plant lines **62**. In step **716**, chassis **102** is lowered for operation, for example, using the three-point hitch on a tractor, and the implement is pulled along the plant lines. As discussed above, once control system **200** senses in step **716** that it has been lowered at the beginning of a plant line **62**, for example using a weight-on-wheels sensor **218**, inclinometer **234**, or other sensor, the control system **200** switches from a transit mode to an operate mode, which includes the state machine **600** operation illustrated in FIG. **10**.

Because the systems of implement **100** are designed to be automatic once calibrated and set up, for example, including detecting plant lines **62**, side shifting tool arms **300** to follow the plant lines, and to complete the selected working operation, such as weeding, on the field **50**, advantageously no added in-cab controls are required for monitoring or operating implement **100**. The HMI **204** is generally located on the implement **100** and any in-cab controls on the tractor **40** are optional, for example via a wireless device, for example a tablet computer or other handheld or mounted touch screen device, including for optional in-cab observation, changing settings, or initiating or ceasing operation; however, all that is required from tractor **40** to operate implement **100** is navigating across field **50** and raising and lowering the chassis **102** at the beginning and end of the plant lines **62**.

In step **718**, the control system **200**, including machine controller **202** and perception system **270**, perform the processing and control discussed above providing autonomous working of the plant lines **62**. For example, the processing and control includes, but not limited to, detecting plant lines **62**; centering tool arms **300** on plant lines **62**; classifying, assigning confidence, bounding, locating and tracking objects of interest, including the above discussed optional pre-/post-processing functions; following the working surface **58** using lift cylinder **346** of tool arm **300**, and

operating the tool attachment **400** to perform the working operation for the plant lines **62**.

In step **720**, upon reaching the end of the plant lines **62**, the implement **100** is lifted up off the wheels by the tractor **40** pulling the implement. The control system **200** responds by switching from the operate mode to transit mode. In transit mode, control system **200** ceases various operations controlled by machine controller **202** and perception system **270**, including detecting plant lines **62**, following the working surface **58** with lift cylinder **346**, and the operation of the tool attachment **400**. Additionally, any reset functions are completed, for example, recentering the tools arms **300** via side-shift actuator **176**. If the field **50** is not yet completed, then the process continues at step **714** with aligning the implement **100** at the start of additional plant lines **62** and lowering the implement.

While the invention has been illustrated and described in detail in the foregoing drawings and description, the same is to be considered as illustrative and not restrictive in character, it being understood that only illustrative embodiments thereof have been shown and described and that all changes and modifications that come within the spirit and scope of the invention as defined in the claims and summary are desired to be protected.

#### REFERENCE NUMERAL LIST

40	Tractor
50	Commodity Field
52a	Prior Art Bed
52b	New Bed
54	Bed Width
56	Furrow
58	Working Surface/Field-of-View
60	Commodity Plant
62	Line 123 Opening
64	Line Spacing 10"
66	Plant Spacing 10'
70	Weeds
72	Space Between Lines
74	Space Between Plants
80	Plant Center
82	Space Before
84	Space After
90	X-Axis
92	Y-Axis
94	Z-Axis
100	Agricultural Implement
102	Chassis
104	Front Crossbar
106	Rear Crossbar/Toolbar
107	Toolbar Extension
108	End Plate
110	Frame
112	Thrust Plates
114	Cover
116	Hood
118	Tool Mounts [static cultivators]
120	Wheel Assembly
122	Support Brackets
124	Rear Axle
126	Rear Wheel
128	Front Axle
130	Front Wheel/Gauge
132	Front Cantilever
134	Pivot
136	Thrust Plates

138 Wheel Span  
 140 Hitch Receiver  
 142 Bottom Hitch Clevis  
 144 Vertical Slot  
 146 Top Hitch Clevis  
 148 Horizontal Slot  
 150 Hydraulic System  
 152 PTO Driven Pump  
 154 Hydraulic Motor  
 156 Reservoir  
 158 Oil Cooler  
 160 Manifold  
 162 Accumulator  
 164 Main Regulator  
 166 Side Shift Regulator  
 168 Tool Actuator Regulator  
 170 Tool Arm Lift Valves  
 172 Gauge/Pitch Actuator  
 174 Gauge Wheel Valve  
 176 Side Shift Actuator  
 178 Side Shift Valve  
 180 Electrical System  
 182 Alternator  
 184 Power Distribution/Regulation  
 186 Battery  
 188 Oil Cooler Fans  
 190 Safety Strut  
 192 Safety Support  
 194 Pivots  
 196 Plant line Alignment Bar  
 198 Threaded Rod/Screw  
 199 Rod Coupling  
 200 Control System  
 201 Enclosure  
 202 Machine Controller  
 204 HMI  
 206 LAN (Ethernet/Bus)  
 208 WAN Connection  
 210 Hydraulic Controls  
 212 PTO Pump Pressure  
 214 System Pressure  
 216 Motor Pressure  
 218 Gauge Cyl. Pressure Switch  
 220 Side Shift Press  
 222 Lift-Upside Press  
 230 Electric Controls  
 232 Odometer Encoder  
 234 Inclinometer  
 238 Side Shift Position  
 240 Touch Screen  
 242 Setup Page  
 244 Configuration  
 246 Control  
 248 Camera View  
 270 Perception System  
 272 GPU  
 274 Ruggedized Housing  
 280 Convolutional Neural Network  
 282 Input  
 284 Output  
 286 Post Processing  
 288 Plant Map  
 290 Training  
 300 Modular Smart Tool Arm  
 302 Static Mounts  
 304 Static Cultivators  
 306 Raised Position

308 Lowered Position  
 310 Mount  
 312 Sides  
 314 Back Span  
 5 316 Front Span  
 318 Toolbar Passage  
 320 Clamp  
 322 Guides  
 324 Bore  
 10 326 Sleeves  
 328 Adjustment Nut  
 330 Articulating Base  
 332 Linear X-Axis Slide Table  
 334 Linear Bearings  
 15 338 Brackets  
 339 Alignment Bar Opening  
 340 Pivots  
 342 Bottom Linkage  
 344 Top Linkage  
 20 346 Lift Hydraulic Cylinder  
 348 Top Cantilever  
 350 Backbone  
 352 Billet  
 354 Base End  
 25 356 Linkage Mounts  
 358 Tool End  
 360 Tool Mount  
 362 Vision Module Receiving Area  
 364 Precision Mount Features  
 30 366 Ground Follower Mount  
 370 Tool Platform  
 372 Toolbar  
 374 Tool Mount  
 376 Precision Locator Features  
 35 380 Z-Axis Linear Slide Table  
 382 Linear Guides  
 384 Table  
 386 Adjust  
 388 Lock  
 40 390 Ground Follower  
 392 Lever  
 394 Stop  
 396 Roller  
 398 Height Sensor  
 45 399 Lever Pivot  
 400 Tool Attachment  
 402 Base  
 404 Mounting Features  
 406 Bracket  
 50 408 Pivot  
 410 tools—Cultivator  
 412 Arm  
 414 Blade  
 416 Pitch Angle  
 55 418 A/B Open/Close Position  
 420 Actuator  
 422 Pneumatic Damper  
 426 Proportional Solenoid Valve  
 428 Flow Regulator  
 60 430 Housing  
 432 Cover  
 434 Cavity  
 436 Bearing  
 440 Actuator Shuttle  
 65 442 Rack Teeth  
 444 Ends  
 446 Larger Bore

- 448 Bore End
- 450 Smaller Bore
- 452 Bore End
- 460 Pinion Gear
- 462 Body
- 464 Teeth
- 466 Shaft
- 468 Tool Mounting Features
- 470 Plug
- 471 Shoulder
- 472 Stem
- 474 Piston Head
- 476 Sealing Areas
- 478 Valve Receiver Bore
- 480 Fluid Channel
- 482 Recess/Supply Area
- 488 Spring
- 490 Valve
- 492 Valve Shaft
- 494 Bevel
- 496 Port
- 498 Valve Seat
- 500 Vision Module
- 502 Mounting Interface
- 504 Module Housing
- 506 Lamps
- 508 Lamp Mounting
- 510 Camera
- 512 Electronics Package
- 514 Connectors
- 516 Optical Lens
- 518 Dust Lens
- 520 Optics Housing
- 522 Module Housing Lens Protector

The invention claimed is:

1. An control system for an precision agricultural implement, comprising:
  - a controller;
  - a machine vision module in communication with to the controller; and
  - a plurality of sensors in communication with the controller, the plurality of sensors including a lift sensor; and
  - a plurality of actuators in communication with the controller, the plurality of actuators including a plurality of agricultural tool actuators; and
 wherein:
  - the plurality of agricultural tool actuators include a first mode of operation for working a commodity plant field and a second mode of operation for not working a commodity plant field;
  - upon the lift sensor detecting elevating of the implement, the controller selects the second mode of operation for the plurality of agricultural tool actuators; and upon the lift sensor detecting a lowering of the implement, the controller selects the first mode of operation for the plurality of agricultural tool actuators.
2. The control system of claim 1, wherein:
  - the plurality of actuators including a side shift actuator to align an agricultural tool of the implement with at least one plant line; and
  - upon the lift sensor detecting elevating of the implement, the controller operates the actuator to reset an alignment of the agricultural tool of the implement.
3. The control system of claim 2, wherein:
  - the controller and machine vision module detect a plurality of plant lines; and

- upon the lift sensor detecting lowering of the implement, the controller operators the side shift actuator to keep the agricultural tool positioned aligned with the at least one plant line.
- 4. The control system of claim 1, wherein:
  - the machine vision module communicates a plurality of images to the controller and the controller is configured to detect objects of interest in the plurality of images; and
  - the controller is configured to define a coordinate space for locating and tracking the objects of interest relative to the position of at least one of a plurality of agricultural tools of the implement.
- 5. The control system of claim 4, wherein each of the plurality of images are communicated in a plurality of data packets, at least the first of which includes a timestamp for correlating each of the plurality of images with the coordinate space.
- 6. The control system of claim 4, wherein:
  - the plurality of sensors includes an odometer providing data to the controller; and
  - the controller is configured to use the odometer data to correlate and track the relative positions of the at least one of the plurality of agricultural tools and the objects of interest in the coordinate space as the implement traverses the objects of interest.
- 7. The control system of claim 6, wherein the odometer data includes a timestamp to correlate the odometer data with the coordinate space, the timestamp calculated as a function of a first time at which the controller requests data from the odometer and a second time at which the controller receives the data from the odometer.
- 8. The control system of claim 4, wherein:
  - the controller includes a convolutional neural network; and
  - processing the plurality of images to detect objects of interest includes the convolutional neural network classifying commodity plants and providing a bounds and a confidence level for each object of interest.
- 9. The control system of claim 8, wherein:
  - the controller is configured for post-processing of the objects of interest; and
  - the post-processing includes reclassifying an object of interest having at least one of a size of the bounds outside of a selected threshold range and the confidence level below a selected threshold.
- 10. The control system of claim 8, wherein:
  - each of the plurality of images spans at least two plant lines; and
  - the controller is configured to detect objects of interest in each of the at least two plant lines.
- 11. The control system of claim 10, wherein:
  - the controller is configured for post-processing of the objects of interest; and
  - the post-processing includes reclassifying an object of interest based on a relative distance of the object of interest to at least one of a threshold for plant interval spacing and an alignment threshold for the plant line.
- 12. The control system of claim 4, wherein:
  - the controller is configured to classify a subset of the objects of interest as commodity plants; and
  - the controller is configured to operate the plurality of agricultural tool actuators to work a plurality of agricultural tools of the implement on the subset.
- 13. The control system of claim 4, wherein:
  - the controller is configured to classify a subset of the objects of interest as commodity plants; and

23

the controller is configured to operate the plurality of agricultural tool actuators to work a plurality of agricultural tools of the implement around the subset.

14. The control system of claim 13, wherein:

the plurality of agricultural tools includes pairs of cultivator blades that straddle a plant line and the plurality of agricultural tool actuators operate to open and close each pair of cultivator blades; and

the controller is configured to operate the plurality of agricultural tool actuators to open each pair of cultivator blades to a first distance before traversing one of the commodity plants and close each pair of cultivator blades a second distance after traversing the one of the commodity plants.

15. The control system of claim 14, wherein the controller is configured to operate the plurality of agricultural tool actuators to keep at least one of the pairs of cultivator blades open upon the controller determining a rate of traversing the commodity plants is too great to detect and track the commodity plants and open each pair of cultivator blades before traversing one of the commodity plants.

16. The control system of claim 14, wherein the controller is configured to operate the plurality of agricultural tool actuators to keep at least one of the pairs of cultivator blades open upon the controller determining a subsequent commodity plants is too close to the one of the commodity plants to close and again open the pair of cultivator blades before traversing subsequent commodity plant.

17. The control system of claim 4, wherein:

the controller is configured to classify a subset of the objects of interest as not commodity plants; and

the controller is configured to operate the plurality of agricultural tool actuators to work a plurality of agricultural tools of the implement on the subset.

18. The control system of claim 1, wherein:

the plurality of actuators includes at least a first lift actuator for translating at least a first one of a plurality of agricultural tools of the implement along a vertical axis and at least a second lift actuator for translating at

24

least a second one of the plurality of agricultural tools of the implement along the vertical axis;

the plurality of sensors includes a first ground following sensor coupled with the at least first one of a plurality of agricultural tools, the first ground following sensor providing first data to the controller based on the position of the at least first one of the plurality of agricultural tools relative to a first working surface of a field;

the plurality of sensors includes a second ground following sensor coupled to the at least second one of the plurality of agricultural tools, the second ground following sensor providing second data to the controller based on the position of the second one of the plurality of agricultural tools relative to a second working surface of the field; and

the controller is configured to operate independently the at least first lift actuator based at least in part on the first data to maintain a preset vertical position of the at least first one of the plurality of agricultural tools relative to the first working surface of the field, and the at least second lift actuator based at least in part on the second data to maintain the present vertical position of the at least second one of the plurality of agricultural tools relative to the second working surface of the field.

19. The control system of claim 1, further comprising an electrical generator; and wherein:

the implement includes a hydraulic system including a power-take-off driven hydraulic pump for powering a hydraulic system; and the hydraulic system drives the electrical generator.

20. The control system of claim 1, further comprising a user interface in communication with the controller.

21. The control system of claim 20, wherein selectable parameters of the controller via the user interface include at least one of commodity plant type, plant interval spacing, plant line spacing, and plant safe zone thresholds.

\* \* \* \* \*